DTU Library

Developing Virtual Power Plant for Optimized Distributed Energy Resources Operation and Integration

You, Shi

Publication date:
2010

Document Version
Publisher's PDF, also known as Version of record

Technical University of Denmark

Shi You

Developing Virtual Power Plant for Optimized Distributed Energy Resources Operation and Integration

PhD Thesis, September 2010

DTU Electrical Engineering
Department of Electrical Engineering

Shi You

Developing Virtual Power Plant for Optimized Distributed Energy Resources Operation and Integration

PhD Thesis, September 2010

Developing Virtual Power Plant for Optimized DER Operation and Integration

Author(s):
Shi You

Supervisor(s):
Associate Professor, Chresten Træholt, Technical University of Denmark
Associate Professor, Bjarne Poulsen, Technical University of Denmark

Department of Electrical Engineering
Centre for Electric Technology (CET)
Technical University of Denmark
Elektrovej 325
DK-2800 Kgs. Lyngby
Denmark

www.elektro.dtu.dk/cet
Tel: (+45) 45 25 35 00
Fax: (+45) 45 88 61 11
E-mail: cet@elektro.dtu.dk

Release date:	September 2010
Class:	public
Edition:	4
Comments:	This report is a part of the requirements to achieve PhD at Technical University of Denmark.

ABSTRACT

Distributed **E**nergy **R**esources (DER) are small-scale power generation and storage technologies, (typically in the range of a few kWe to tens of kWe) located close to the customer side. They are right now under heavy development and have a great market potential in the near future. However, these sources are usually deployed in way of “fit and forget” which to a great extent confines their value and presents challenges in relation to:

- Optimized DER operation related to time varying onsite demand requirements, ambient conditions and electricity prices, etc.
- Coordinated control of many small units in the electric power system
- Efficient electricity market participation to benefit both power system operation and DER owners

To address these issues, an innovative concept **V**irtual **P**ower **P**lant (VPP) is investigated in this PhD study. Based on a comprehensive overview of the state of the art of VPP, the **M**arket-**B**ased VPP (MBVPP) concept is proposed. The function-based MBVPP provides a generic and flexible solution for the DER integration by connecting the DER to the bulk power system operation via market participation.

Two schemes for managing the DER generation and trading portfolios, direct control and price signal control have been discussed and simulated. Due to their prevalence and controllability, the µCHP systems are modeled to represent the general DER technology in the corresponding studies. For the direct controlled VPP, all the µCHP units are optimally controlled by the VPP operator based on forecasted market and demand information. For the proposed price signal scheme, an **A**rtificial **N**eural **N**etwork (ANN) is developed to characterize and estimate the price responsiveness of a µCHP group. It is found that although the prognosis result is relatively good, the price signal controlled scheme is still challenged by many uncertainties which reside in the nature of price signal control such as jumpy response.

To demonstrate the feasibility of the VPP, a prototyped VPP with two Dachs µCHP systems is set up in the laboratory as a proof of concept. It has shown that, on the premise of an advanced **I**nformation and **C**ommunication **T**echnology (ICT) infrastructure, the VPP represents a feasible solution to be implemented.

RESUMÉ

Med **D**istribueret **E**nergi **R**esurser (DER) refereres til små skala el-kraftproduktion (typisk i størrelsesordenen få kWel op til tocifret kWel) som er placeret tæt på forbrugerside. Området er inde i en rivende udvikling og udgør et stort markedspotentiale i den nære fremtid. Enhederne udrulles oftest efter devisen ”tilslut og glem (dem) så”, hvilket i høj grad begrænser enhedernes værdi og medvirker til at øge udfordringerne i forhold til:

- Optimal drift af DER enheden i forhold til varierende lokalt forbrug, de klimatiske rammebetingelser og prisen på elektricitet
- Koordineret styring af mange små enheder i det elektriske net/system
- Effektiv markedsintegration af enhederne med deraf fordel for både DER ejer og system operatørerne

For at adressere nævnte problemstillinger afdækkes konceptet ”et virtuelt kraftværk” (**V**irtual **P**ower **P**lant = VPP) i dette PhD studie. Baseret på en grundig gennemgang af ”state-of-the-art”, foreslås det innovative koncept: ”Markedsbaseret VPP” (MBVPP). Dette funktionsbaserede MBVPP tilbyder, via en markedsintegration, en generisk/naturlig og fleksibel integration af DER enhederne i driften af det overordnede elektriske system.

To metoder til at styre DER enhedernes produktions- og markedsporteføljer er behandlet og simuleret, dels den direkte styring og dels en prisebaseret styring. På grund- mikrokraftvarmeenhedernes (µCHP) udbredelse, tekniske mangfoldighed samt deres styrbarhed, er denne type enhed valgt som model DER i dette studie. For et direkte styret VPP, bliver alle µCHP enhederne styret optimalt af VPP kontrolleren på grundlag af markeds forudsigelser og forventet efterspørgsel. For tilfældet med prisbaseret styring er der udviklet et kunstigt neuralt netværk (ANN), for dels at karakterisere, dels estimere prisfølsomheden af en gruppe af µCHP’er. Det har vist sig at selvom prognoserne er forholdsvis sikre, udgør prisstyringens usikre natur stadigvæk en udfordring, såsom f.eks. et trinrespons.

For at demonstrere brugbarheden af VPP, er et prototype VPP opbygget i laboratoriet med to µCHP som en slags ”proof of concept”. Det har vist sig at under forudsætningen af at en avanceret ICT infrastruktur er til rådighed, da er muligt at implementere et VPP uden synderlige tekniske barrierer.

PREFACE

This thesis was prepared at the **C**enter for **E**lectric **T**echnology (CET), Department of Electrical Engineering of **T**echnical **U**niversity of **D**enmark (DTU) in partial fulfillment of the requirements for the Ph. D degree in Denmark. It was financed by the Danish PSO program run by Energynet.dk, for which I am grateful.

This research project would not have been possible without the support of many people. Herewith I am heartily thankful to my supervisors Associate Professor Chresten Træholt and Associate Professor Bjarne Poulsen who have been abundantly helpful and offered me invaluable assistance, support and guidance from the initial to the final. Deepest thanks go to Professor Jacob Østergaard, thank you very much for proposing this innovative idea and giving me the opportunity to work at CET with so many good colleagues.

My colleagues at CET are excellent. The special thanks of mine must go to Peter Bach Andersen, Anders Bro Pedersen and Einar Bragi Hauksson, who have helped me to learn the **I**nformation and **C**ommunication **T**echnology (ICT) knowledge from scratch and set up the current demonstration in the laboratory. Equally, I must thank my other colleagues, Preben Nyeng, Kai Heussen, Arshad Saleem, and Yu Chen and many others for valuable discussions and interesting collaborations throughout the presented work. Further, I must appreciate the consistent care and help from Lousie Busch.Jense, who has made my living in Denmark much easier.

I would also like to thank all the industrial partners: EC Power A/S, Danfoss A/S and Syd Energi, for their generosity of sharing their practical knowledge and experience.

Last but not least, to my dear family, I must thank you for your understanding and endless love through the duration of my studies.

TABLE OF CONTENT

ACRONYMS AND ABBREVIATIONS

AD	Active Demand
ADSL	Asymmetric Digital Subscriber Line
AMI	Advanced Meter Infrastructure
AMR	Automated Meter Reading
ANN	Artificial Neural Network
BP	Backpropagation
CCS	Central Control System
CET	Central for Electric Technology
CHP	Combined Heat and Power P-lant
CPP	Critical Peak Pricing
CVPP	Commercial Virtual Power Plant
DEMS	Distributed Energy Manageme-nt System
DER	Distributed Energy Resources
DMS	Distribution Management Syste-m
DR	Demand Response
DG	Distributed Generation
DSO	Distribution System Operator
ECN	Energy Research Centre of the Netherlands
EES	Electric Energy Storage
ISO	Independent System Operator
EMS	Energy Management System
EU	European Union
FB	Fenix Box
FC	Fuel Cell
FENIX	Flexible Electricity Network to Integrate the Expected Energy Solution Project
GAMS	General Algebraic Modeling System
GPRS	General Packet Radio Service
GSM	Global System for Mobile Com-munications
GUI	Graphical User Interface
HAN	Home Area Network
HEMS	Home Energy Management Sys-tem
HHV	Higher Heating Value
HVAC	Heating, Ventilation and Air Con-ditioning
ICE	Internal Combustion Engine
ICT	Information and communication Technology
IEC	International Electrotechnical C-ommission
TOU	Time of Use

L/A	Lead-acid
LHV	Lower Heating Value
LMP	Locational Marginal Price
LSVPP	Large Scale Virtual Power Plant
MAPE	Mean Absolute Percentage Error
MBVPP	Market-based Virtual Power Plant
MIP	Mixed Integer Programming
MMS	Manufacturing Message Specification
MPC	Model Predictive Control
MSE	Mean Square Error
Na-S	Sodium-sulfur
Ni-MH	Nickel-metal hydride
NG	Natural Gas
PEMFC	Proton Exchange Membrane Fuel Cell
PLC	Power Line Carrier
PV	Photovoltaic
REST	Representational Sate Transfer Service
RRC	Radio Ripple Control
RTP	Real-time Pricing
RTU	Remote Terminal Unit
SCADA	Supervisor Control and Data Acquisition
SOA	Service Oriented Architecture
SOFC	Solid Oxide Fuel Cell
TSO	Transmission System Operator
TVPP	Technical Virtual Power Plant
UCTE	Union for the Coordination of the Transmission System
UI	Unscheduled Interchange
UK	United Kingdom
URL	Uniform Resource Locator
UTMS	Universal Mobile Telecommunication System
VFCPP	Virtual Fuel Cell Power Plant
VPN	Virtual Private Network
VPP	Virtual Power Plant
VU	Virtual Utility
WADE	World Survey of Decentralized Energy

SYMBOLS

Symbol	Unit	Definition
$h_{chp,i}(t)$	kWh	Heat produced by µCHP unit *i* during time interval *t*
$h_{chpmin,i}$	kW	Minimum heat output of µCHP unit *i*
$h_{chpmax,i}$	kW	Maximum heat output of µCHP unit *i*
$h_{b,i}(t)$	kWh	Heat produced by boiler *i* during time interval *t*
$h_{f,i}(t)$	kWh	Heat flowed out of the heat tank *i* during interval *t*
$h_{d,i}(t)$	kWh	Heat demand of household *i* during time interval *t*
$h_{s,i}(t)$	kWh	Initial heat stored in the heat tank *i* during interval *t*
$h_{smax,i}$	kWh	Maximum storage capacity of heat tank *i*
$h_{smin,i}$	kWh	Minimum storage capacity of heat tank *i*
$e_{chp,i}(t)$	kWh	Electricity produced by µCHP unit *i* during interval *t*
$e_{chpmin,i}$	kW	Minimum electricity output of µCHP unit *i*
$e_{chpmax,i}$	kW	Maximum electricity output of µCHP unit *i*
$e_{d,i}(t)$	kWh	Electricity demand of household *i* during time interval *t*
$e_{grid,i}(t)$	kWh	Electricity exchanged with the external grid of household *i* during time interval *t*
$e_{im,i}(t)$	kWh	Electricity imported from the grid of household *i* during time interval *t*
$e_{ex,i}(t)$	kWh	Electricity exported from the grid of household *i* during time interval *t*
$f_{chp,i}(t)$	kWh	Fuel input of µCHP unit *i* during time interval *t*
$f_{chpmin,i}$	kW	Minimum fuel input of µCHP unit *i*
$f_{chpmax,i}$	kW	Maximum fuel input of µCHP unit *i*
$f_{b,i}(t)$	kWh	Fuel input of boiler unit *i* during time interval *t*

$f_{bmin,i}$	kW	Minimum fuel input of boiler unit *i*
$f_{bmax,,i}$	kW	Maximum fuel input of µCHP unit *i*
$o_i(t)$	/	Binary variable indicating the on (1)/off (0) status of µCHP unit *i*
$a_{1,i}, b_{1,i}, a_{2,i}, b_{2,i}$	/	Parameters describing the generation characteristics of µCHP unit *i*
$\eta_{chp,i}$	/	Overall energy efficiency of µCHP unit *i*
$\eta_{chpel,i}$	/	Electrical efficiency of µCHP unit *i*
$\eta_{chpth,i}$	/	Thermal efficiency of µCHP unit *i*
T	/	Total number of time intervals considered in one optimization
Δt	hour	Time length one simulated time interval
$cost_i(t)$	DKK	System cost for household *i* during time interval *t*
$\pi_f(t)$	DKK/kWh	Fuel price during time interval *t*
$\pi_{im}(t)$	DKK/kWh	Electricity import price during time interval *t*
$\pi_{ex}(t)$	DKK/kWh	Electricity export price during time interval *t*
$cost_{vpp}(t)$	DKK	System cost for VPP during time interval *t*
$cost'_{vpp}(t)$	DKK	System cost for VPP after redispatch during time interval *t*
$\pi_e(t)$	DKK/kWh	Electricity price posted by VPP
$e_{vpp}(t)$	kWh	Electricity exchanged with grid of VPP during time interval *t*
$e'_{vpp}(t)$	kWh	Electricity exchanged with grid of VPP after redispatch during time interval *t*
$\pi_{e,up}(t)$	DKK/kWh	Balancing price for up regulation during time interval *t*
$\pi_{e,down}(t)$	DKK/kWh	Balancing price for down regulation during time interval *t*
$e_{chp,i}{}'(t)$	kWh	Electricity produced by µCHP unit *i* after redispatched
$f_{vpp}(t)$	kWh	The fuel consumption of VPP during time interval *t*
$f'_{vpp}(t)$	kWh	The fuel consumption of VPP after redispatch during time interval *t*
$\Delta P(t)$	kWh	Internal unbalance during time interval *t*
$\Delta P'(t)$	kWh	Real unbalance between the scheduled exchange and the real exchange during time interval *t*
$h_{d,vpp}(t)$	kWh	Total heat demand of VPP during time interval *t*
$e_{d,vpp}(t)$	kWh	Total electricity demand of VPP during time interval *t*

$u(t)$	/	Four-element input vectors of NN
$y(t)$	/	Single-element output vector of NN (real target values)
y'	/	Single-element output vector of NN (estimated values)
k	/	Number of time delays

1 INTRODUCTION

The origin of the terminology “**V**irtual **P**ower **P**lant (VPP)” can be traced back to 1997, when Doctor Shimon Awerbuch, in his book “The Virtual Utility: Accounting, Technology& Competitive aspects of the Emerging Industry”, defined the Virtual Utility as:

> The **V**irtual **U**tility (VU) is a flexible collaboration of independent, market-driven entities that provide efficient energy service demanded by consumers without necessarily owning the corresponding assets.

Just like the VU which aims to take advantage of the emerging technologies and provide customer-oriented energy service, the idea of VPP is to aggregate different types of **D**istributed **E**nergy **R**esources (DER) through an advanced ICT infrastructure for the better use of those available resources. With properly designed aggregation methods, potential benefits could be easily achieved. These benefits can be:

- Offering considerable saving for primary energy and reduction in the emission of pollutants.
- Reducing the energy losses during electricity transmission and distribution, resulting in additional energy saving.
- Facilitating the integration of intermittent generation technologies based on renewable energy resources like wind power or **P**hoto**v**oltaic (PV), etc. by stabilizing the stochastic power output
- Enabling the delay of investment on enforcing the electrical infrastructure as implementing the VPP requires relatively little modification to existing infrastructure.
- Providing value-added services like ancillary services to power system operation through centralized/coordinated control strategies to both maintain the reliability, security and to increase the flexibility of electricity supply.
- Increasing the participation of the end users in both electricity market transactions and power system operations with more degrees of freedom.
- Representing a wide range of options towards a future smart grid.

In this PhD thesis, the study on the innovative idea “VPP” is presented.

1.1 Background

Traditional power grids are predominately based on large central power stations which are connected to high voltage transmission systems and then supply the power to the end users through medium and low voltage distribution systems. Such an overall picture with one direction of power flow has not been changed for decades and has presented the following characteristics:

- Relatively low energy efficiency: almost 60 percent of the primary energy is wasted in the form of heat during generation, transmission and distribution [a1]
- Very high emission level: fossil-fuel power plants meet most of the electricity demand and are responsible for a large fraction of carbon dioxide emissions worldwide [w1]
- Generation located in rather concentrated area: this requires a relatively high redundancy level in order to maintain the security supply.
- Passive distribution network: the resources like active demand and backup generators connected to the distribution network hardly contribute to system operation.

Recently, a great amount of **D**istributed **G**enerations (DGs) have been emerging in the power system to complement the previous way of power supply. First of all, as they are placed closer to the end users, the overall energy loss through the transmission system is considerably reduced. Secondly, the deployment of DG normally defers the need for grid renewal. Thirdly, they could also increase the grid reliability and power quality [a3][b1]. Besides, the climate concern and the primary energy depletion are another two driving factors behind the fast growth of DG [a2]. Since many DG units are either driven by renewable resources like wind or having much higher energy efficiencies like **C**ombined **H**eat and **P**ower plants (CHPs), it is commonly agreed that the growth of DG penetration will make a significant contribution to sustainable development. **Figure 1-1** from the World Survey of Decentralized Energy (WADE 2006) [r1], illustrates the penetration level of DG for various countries in 2006, wherein Denmark took the leading position due to a vast amount of CHPs and wind power plants which had been continuously deployed since early nineties.

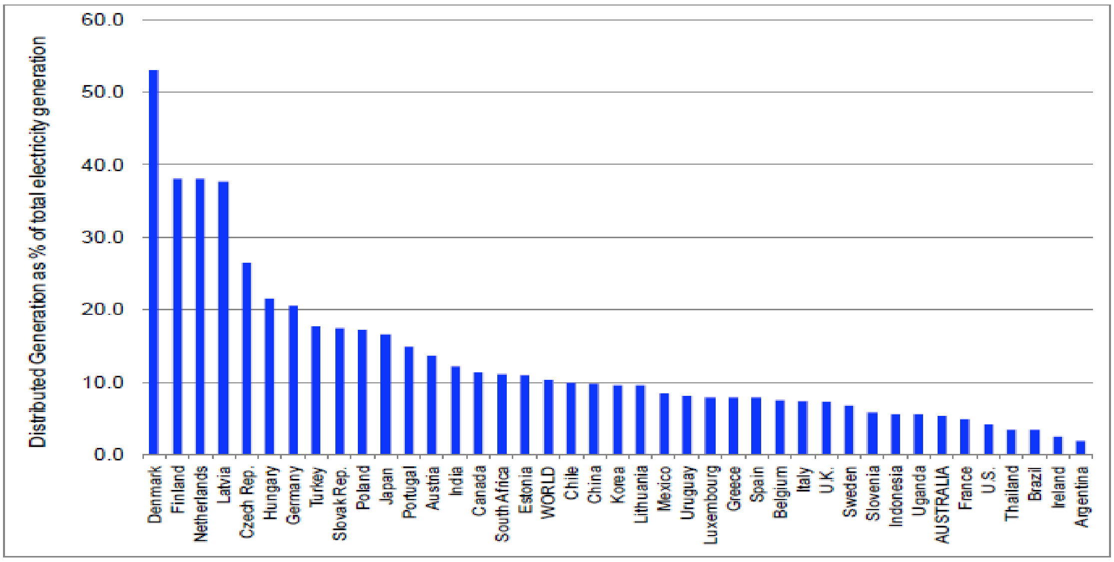

Figure 1-1: Proportion of electricity from distributed generation (WADE 2006)

Today, the trend for developing DG technologies is continuing and the sizes for many DG units turn to be much smaller, which makes them suitable for either residential use or small commercial applications. Together with small-scale active demand and energy storage technologies, these DG technologies are referred as **D**istributed **E**nergy **R**esources (DER) (typically less than 250 kW [a56][r2]) in order to distinguish them from other DG technologies with bigger size (from hundreds of kW to hundreds of MW). Although many DER technologies, e.g. micro-CHP (µCHP), solar panels and Electric Vehicles (EV), are still quite expensive for most consumers, the wide spread use of the DER have already been observed due to the governmental policy support and technology innovations. In Japan, over 90,000 fuel cell based µCHP units were already deployed in 2009 with a very strong incentive, and half of the cost for the µCHP unit was covered by the government on each purchase [a5]. While in Germany, new CHP act 2008 focuses on new installations being brought into operation by the end of 2014 [b2]. For CHP unit rated less than 50kWe, the CHP owner receives 5.11 eurocents per kWh regardless of whether the power is produced for his own use or for public consumption. Moreover, fuel used by µCHP systems is exempt from the energy tax indefinitely [w2].

Despite there are tremendous benefits brought by the DER, many challenges arise along with the ever-increasing number of deployed units. For example, the power flow may reverse as the generation capacity of one area with a number of DER exceeds the local demand. Such reverse power flow not only challenges the conventional protection schemes, but also can result in network congestions. In addition to the technical concerns, the current “fit and forget” operation schemes together with the capacity barriers of the current electricity markets further impede the activeness of the DER in power system operation. To tackle these issues, updating the current electrical and ICT infrastructure and calling for well designed integration strategies are both required. To develop the corresponding solutions, integrated approaches, covering technical, commercial and regulatory factors should be taken into account [a4]. Criteria for such design must be set to maximize the benefits brought by the DER without jeopardizing the security and reliability of power supply and affecting the profits of other parties. Consequently, the DER should play an active role in the grid operation and energy supply.

It is interesting to note that, Microgrid and VPP, among many innovative paradigms in facilitating the integration of the DER, are two of the attractive conceptual solutions which provide coordination and aggregation for the DER. The Microgrid, defined by [a56][r3], is constituted by the DER and multiple electrical loads. It can operate as a single autonomous grid, which is connected to or “islanded” from the existing utility power grid. While the VPP, without a firm definition yet, represents an “Internet of Energy” developed on the basis of advanced ICT. Therefore the geographically allocated DER can be coordinated together to maximize their values for both the end-users and the power system operators. Literally, a Microgrid manages both the generation assets, demand side and network assets inside it, while a VPP is only in charge of the generation assets. However, since both concepts have one common critical feature: the ability to aggregate the DER on the distribution level, a VPP could also be seen as a cluster of Microgrids. In turn, a Microgrid could also include some VPP-like entities running under its pre-defined operation schemes.

1.2 Research objective of the VPP Project

This three-year PhD research project “Developing Virtual Power Plant for Optimized DER Operation and Integration” was initiated by CET at the DTU in collaboration with the µCHP system manufacturers EC Power A/S, Danfoss (now Dantherm) and one of the largest Danish utility companies SYD Energi.

This research project deals with the active participation of the DER, mainly µCHP systems, in the electricity infrastructure through a VPP like framework. The objective is to provide a solution that facilitates the exploitation of the potential benefits of the DER based on a generic VPP concept.

To reach this objective, following research concerns have been studied within the project.

1. What is the VPP and what is the state of the art of VPP?
   Although it is now over a decade since the VPP became a significant and topical phenomenon in power systems, there is as yet no universal agreement on the definition of VPP. This is particularly due to the diversity of the aggregation methods, the DER technologies and the needs of the developers.

To answer this question, the previous and ongoing VPP studies have been intensively reviewed in Chapter 2, which also describes the fundamental components of the VPP.

2. How to develop a generic VPP concept which benefits all parties?
Due to the variety of the VPP design, a generic VPP solution needs to be developed to provide the optimized operation and seamless integration of the DER, regardless of their types. Moreover, shareholders like VPP operators and power system operators should also benefit from this aggregated operation.

In this thesis, the market-based operation is considered as the generic objective for the VPP operation since almost all human involved activities today related to power system operation are market driven. To elaborate the current market environment, the Nordic power market is introduced in Chapter 3, following which a market-based design of the VPP is presented. To further increase the flexibility, such design possesses comprehensive functionalities that can be easily removed or added under different conditions.

3. How can the VPP efficiently control/coordinate the operation of the DER?
The generality introduced by market-based design establishes the essential linkage between the DER operation and the power system operation. However, there are still many choices on how to control/coordinate the operation of the DER from centralized control structures to decentralized control structures.

The emphasis regarding the control schemes is put on the direct control scheme and price signal control scheme in Chapter 4 and Chapter 5, respectively.

4. How to implement and test the proposed market-based VPP concept in a real life?
Although there are various ways mentioned in literature on implementing the VPP in a real life, it is still a very challenging task to implement and test this pioneering concept.

To demonstrate the feasibility of the proposed VPP concept and its functionalities, an experimental setup at CET was built. The IEC 61850 standard, and especially its data model, was used for the communication between DER and VPP. In Chapter 6, the ongoing setup is depicted.

1.3 Outline and contributions

This thesis comprises 7 chapters.

Chapter 2, ***State of the Art of VPP***, starts with an overview of different DER technologies which are the basic components of any VPP. Afterwards, recent technologies, such as the smart metering and the **H**ome **E**nergy **M**anagement **S**ystems (HEMSs), which further facilitate the active involvement of DER in the electricity market transactions, power system operations and the VPP-like framework, are briefly explained. Furthermore, the state of the art of VPP technologies is presented. Even though the core of the VPP concept can be summarized by a single word "aggregation", a variety of designs of the VPP do exist. Finally, a variety of designs of the VPP are classified into different categories to better understand the essence of the VPP.

Chapter 3, ***Developing Market-based VPP***, describes the market-based design of the VPP. This is considered as the generic way of developing a VPP. Firstly, the Nordic power market is introduced as the ambient for the market-based operation scheme. Secondly, the system architecture for a market-based VPP is designed to illustrate the internal configuration of the VPP, the interaction with external parties as well as the operational principles and procedures. Thirdly, different control strategies for market-based VPP operations are described and compared. In the end, a flexible function-based design for the market-based VPP is presented.

Chapter 4, ***Direct Controlled VPP***, introduces the optimized operation scheme for a direct controlled VPP under present regulated market conditions. First of all, the decentralized operation of the prosumers with least-cost controlled µCHP systems is modeled, which provides a reference for the proposed VPP scheme. Subsequently, one µCHP systems constituted VPP, which intends to optimize its generation and trading portfolios, is modeled, simulated and analyzed.

Chapter 5, ***Price Signal Controlled VPP***, proposes to use the price signals to coordinate the DER operation. The theory of price signal control for different resources is introduced at the beginning of this chapter. Afterwards, the operation scheme for a price signal controlled VPP is introduced with much more streamlined function requirements. To illustrate the proposed idea, a 100 prosumers constituted VPP is simulated. Each prosumer in this case has a µCHP system installed at his premises. Artificial Neural Network (ANN) technology is applied in this VPP scheme as the identification tool, which helps to characterize the price responsiveness of the prosumer group. In the end, the challenges for the price signal controlled VPP are discussed.

Chapter 6, ***Experimental Setup***, describes the ongoing experimental setup at CET and the future development for the proposed VPP concept.

Chapter 7, ***Conclusion and Future Work***, concludes the dissertation and presents the future work on how the VPP concept can be further developed to cope with the foreseeable challenges.

The contribution of this project is the proposal of a solution for effectively integrating the increasing amount of DER, especially in Denmark. Further, in addition to provide the proof-of-concept demonstration, the laboratory setup could also be used for other purposes such as testing different DER control strategies. It also presents the possibility to extend such a small-scale demonstration into a large-scale one which fits into the European SmartGrid vision for the power system of the future and the research agenda under development.

1.4 Publications

Within the PhD research project, there are six conference papers have been published or submitted, as listed below,

[A] Shi, Y., Chresten, T., and Bjarne, P., A Market-based Virtual Power Plant, in proceedings of the International Conference on Clean Electrical Power, Renewable Energy Resources Impact (ICCEP), 2009, Capri, Italy, pp.460-465

[B] Shi, Y., Chresten, T., and Bjarne, P., A Study on Electricity Export Capability of the µCHP System with Spot Price, in proceedings of the IEEE PES 2009 General Meeting, 2009, Calgary, Alberta, Canada

[C] Shi, Y., Chresten, T., and Bjarne, P., Generic Virtual Power Plants: Management of Distributed Energy Resources under Liberalized Electricity Market, in proceedings of the 8th IET International Conference on Advances in Power System Control, Operation and Management, 2009, Hong Kong, P.R. China,

[D] Shi, Y., Chresten, T., and Bjarne, P., Is micro-CHP Price Controllable under Price Signal Controlled Virtual Power Plant, Submitted to the 2nd conference on Innovative Smart Grid Technologies, Anaheim California

[E] Shi, Y., Chresten, T., and Bjarne, P., Economic Dispatch of Electric Energy Storage with Multi-service Provision, Accepted by the 9th International Power and Energy Conference, 2010, Singapore

[F] Qin, N., Zhao, X., Shi, Y., and Vladislav, A., Offshore Wind Farm Connection with Low Frequency AC Transmission Technology, proceedings of the IEEE PES 2009 General Meeting, 2009, Calgary, Alberta, Canada

Papers A, B, C, D directly contribute to the VPP research. Paper A and C contribute to the design of market-based VPP which is elaborated in Chapter 3. Paper B proposes a generic model for optimized operation of µCHP system under the hourly spot prices and simulates the economic benefits for µCHP owners. This model and the corresponding result provide the reference for the simulated VPP applications with different control schemes, which are explained in Chapter 4 and Chapter 5. Paper D analyzes the price responsiveness of the µCHP systems with different generation characteristics.

Paper E develops a generic optimization model that explores the difficulty met by Electric Energy Storage (EES) when to achieve multiple value streams. The proposed algorithm can also be applied to VPP-related applications.

Paper F presents a feasibility study of using low frequency AC transmission technology for offshore wind farm connection, which is irrelevant to the VPP research but enriches the PhD study.

In Appendix D, papers [A]-[E] are attached for readers' convenience.

2 STATE OF THE ART OF VIRTUAL POWER PLANT

The idea of VPP is to address the integration issues related to DER through aggregation. Since VPP is more software dependent and can be implemented under current regulatory structures, more and more attention has been paid to this idea in recent years. This chapter aims to address the first research question "what is the VPP and what is the state of the art of it" by providing the readers with comprehensive information about the VPP from its fundamental components to its various developments. In section 2.1, several types of the DER, which form the most basic components of a VPP, are briefly reviewed. Technical concerns and market concerns related to the DER development are also shortly presented. In section 2.2, smart metering which represents the communication interface between DER and VPP is shortly introduced. The **H**ome **E**nergy **M**anagement **S**ystem (HEMS) which enables the utilization of a mini-VPP alike smart house is explained in the same section. In section 2.3, the state of the art of VPP technologies is thoroughly presented. In section 2.4, summary and discussions are given.

2.1 Technologies of Distributed Energy Resources

DER are normally referred as small-scale generation and storage technologies. Because the active demand [1] (also in small-scale) can make the same contribution to help the power system operation as the generation/storage technologies do, it is also included in the category of DER. Although the common problem for the most DER is their high costs, they still show very obvious benefits over conventional generation technologies. Thus, they have drawn many attentions from different parties. These benefits include high efficiency and flexibility of fuel usage, short construction lead time and relatively low emission, high power quality and energy independence [b1].

In this section, several typical DER categories: µCHP system, electric energy storage, photovoltaic systems, wind turbines and active demand are briefly reviewed. Many other DER technologies such as microturbines, diesel engines which function as prime movers are not described in this part as they have similar working principles and harness energy through burning fossil fuels or biofuels. Recent concerns related to the in-

[1] Demand response (DR) might be a more familiar nomenclature than Active demand (AD). However, DR is referred to the mechanisms/programs used to regulate the AD; while AD is the resource which responds to DR.

crease of DER penetration is shortly reviewed, which further proves the need for VPP-like active management systems.

2.1.1 Micro-combined heat and power system

µCHP system is an extension of the conventional cogeneration technology, which supplies both electricity and heat to domestic houses and small commercial buildings. By capturing the “wasted heat”, the overall energy efficiency can reach up to 90%. Although there is no consistent definition regarding the term “Micro”, the definition given by EU Cogeneration Directive is commonly accepted which defines µCHP as units up to 50kW electrical output [a6]. A key parameter for all µCHP system is the power to heat ratio (P to H in **Table 2-1**) which reflects the proportion of electric output under different operating status. As shown in **Figure 2-1**, studies reveal that the higher the power to heat ratio the greater the potential carbon savings for a given energy input.

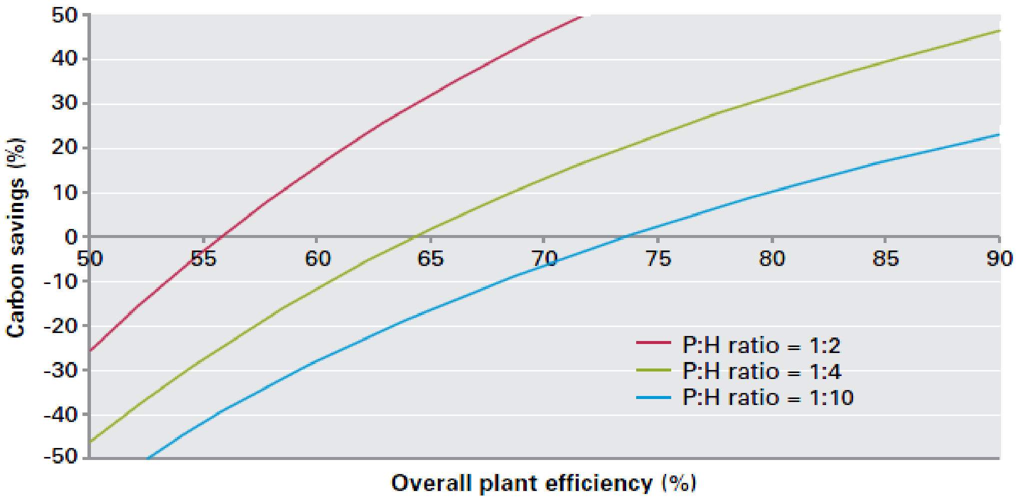

Figure 2-1: Theoretical carbon savings for different power-to-heat ratios [r4]

The most popular prime mover technologies applied to µCHP applications include: **I**nternal **C**ombustion **E**ngines (ICEs), Stirling engines, and **F**uel **C**ells (FCs). A comparison of the µCHP systems based on different prime mover technologies is given in **Table 2-2**.

Table 2-2: Comparison of prime mover technologies for µCHP systems.

Criteria	ICE	Stirling Engine (SE)	Fuel Cell (FC)
Technology maturity	Commercialized	Commercialized, but still in development	In development but with prototypes available
P to H ratio	1:2-1:3	1:4-1:10	1:0.4-1:1.5

Overall Efficiency % (LHV) [2]	85-90%	90-95%	80-90%
Life	>40,000hours	>100,000hours	Around 6,000hours
Responsiveness	On the order of seconds	On the order of minutes	Minutes to hours

ICE based µCHP systems are well known for their well-proven technology, robust nature, and reliability. Typical spark ignition (Otto-cycle) engines are used in these systems, which are comparable to those used in vehicles [b2]. Compared with the other µCHP systems, the capital cost for ICE based µCHP systems is relatively lower. Disadvantages of this kind of µCHP systems include frequent maintenance and relatively high noise and vibration level. Further, the part load efficiency of ICE based µCHP systems is poorer than those driven by the other two prime mover technologies.

Stirling engine are external combustion engines, working by cyclic compression and expansion of a sealed working gas at different temperatures such that it achieves the energy conversion from heat to mechanical power. Although these µCHP systems are not widely used yet, they have very good market potential because of their prospects for high efficiency, good performance at partial load, fuel flexibility and low noise/vibration levels. Being an emerging technology without mass production, the cost for Stirling engine based µCHP systems is normally much higher than ICE based µCHP systems.

FC based µCHP systems generate electricity through the chemical reaction of combustion. Generally the fuel like hydrogen is separated into electrons and ions by catalyst at the anode. The electrolyte membranes set between the anode and cathode only allow ions crossing, which forces the electrons to move through an external circuit and produce electricity. Once the ions reach the cathode, they are reunited with the electrons and a third chemical, usually oxygen, through another chemical reaction at the cathode to complete the process. The waste heat produced from reformer and fuel cell stack is harnessed for space heating and water heating. For different Fuel Cell technologies, the start-up time varies from minutes to hours. For instance, µCHP systems based on **L**ower **T**emperature **P**roton **E**xchange **M**embrane **F**uel **C**ell (LTPEMFC) which requires a low operating temperature around 80°C can execute a cold start-up within minutes. For µCHP systems based on Solid Oxide Fuel Cells (SOFC) which requires a high working temperature around 800°C need 10-20 hours to heat up the fuel from cold state. The advantages of fuel cell based µCHP systems include almost zero emission, potential for

[2] Heating values are expressed as higher or lower heating values (HHV or LHV), representing the amount of heat released during combustion. The difference between HHV and LHV is simply whether the product water is in the liquid phase (HHV), or the gaseous phase (LHV).

high electric efficiency and excellent part load efficiency. Due to the high cost and relatively short lifetime of fuel cell based µCHP systems, they can hardly compete with other technologies. However, many supports from the governments have been made to promote this technology due to the climate concerns and the promises related to high electrical efficiency.

By 2005, there were only about 100 µCHP units installed in Denmark due to the existence of large citywide district heating networks [a7]. However, because of its great potential for CO_2 reduction, recent study [a8] has estimated the µCHP market potential in Denmark, especially the fuel cell based µCHP, can reach around 2200MWe. This corresponds to 8.5% of the current electricity generation in Denmark. In addition to meeting the demand increase, this amount of flexible generation can also be either used to replace the conventional coal-fired power plants or to stimulate the increase of wind power penetration.

2.1.2 Electric energy storage

Electric **E**nergy **S**torage (EES) refers to the technologies which are able to store electricity for later use. In addition to providing cost effective usage of electricity, EES is also used to improve power quality by correcting voltage sags, and flickers, or help stabilize the system frequency. In **Figure 2-2**, typical EES technologies are compared over two key factors for EES: rated power and discharge time. Technologies like pumped hydro storage and compressed air energy storage are normally deployed in large scale and have relatively long discharge time up to days. Technologies like batteries cover a wide range of applications as they differ from each other in life time, efficiency and cost, etc. For medium scale battery applications, Na-S and L/A have already been in use for many years; however, the high cost with safety concern for Na-S and short life time for L/A are considered as two biggest disadvantages respectively.

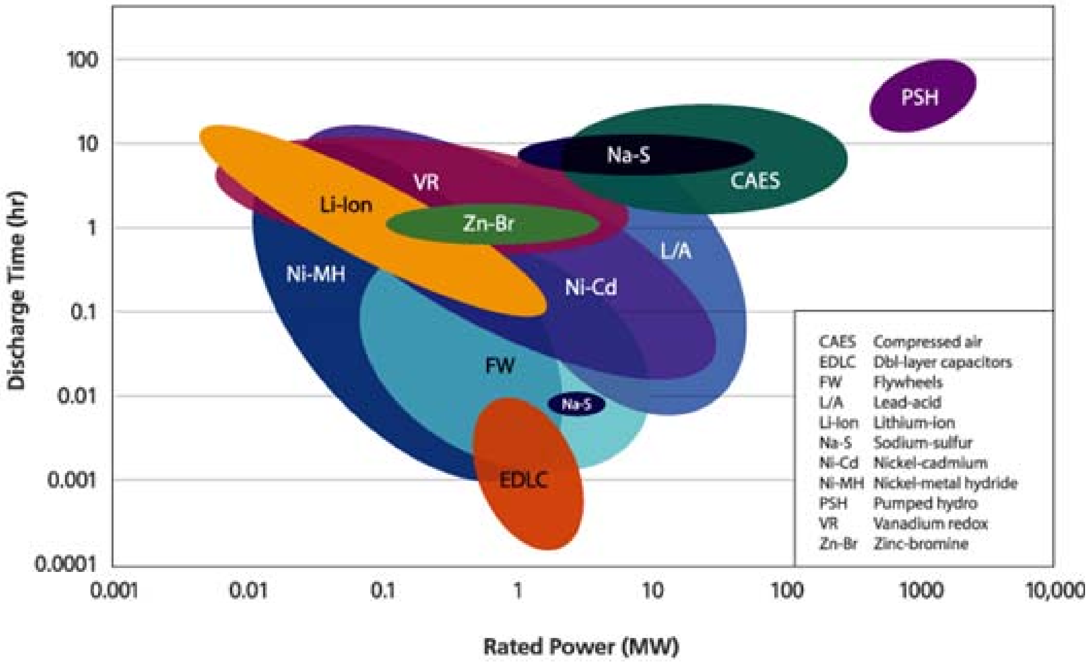

Figure 2-2: Discharge time versus rated power for different EES technologies as of November 2008 (source: **E**lectricity **S**torage **A**ssociation (ESA) [w3])

For DER-like applications of EES, **E**lectric **V**ehicles (EVs) have drawn increasing attention in recent years. Rechargeable batteries based on L/A, Li-ion and Ni-MH have been used for EV applications. It is generally believed that EV will replace a large proportion of gasoline vehicles in the near future [a56][r17].

Apart from EES, electricity can also be stored in the form of hot water. When such thermal storages are used together with cogeneration systems, the heat production and electricity production of cogeneration systems are to some extent decoupled which results in higher system flexibility. Further, thermal storages can absorb electricity surplus and thus reduce the negative impacts coming from intermittent generators like wind turbines and PV systems.

2.1.3 Photovoltaics and wind turbines

PV systems, or solar cells, convert sunlight directly into electricity. Through photovoltaic effect, during which process the electrons of the cell absorb the energy of photons and leave the semiconductor through an external circuit, electricity is generated with no moving parts and emissions. Current PV systems are normally mounted on the roof or into the walls of a building, with the size range of 1kW-100kW and the capacity factor [3] normally under 25% [w4]. However, the high cost of PV systems puts up a lot of barriers for their bulk applications.

[3] Capacity factor of a power plant is the ratio of its actual output over a period of time and its output if it had operated at nominal capacity during that period.

Similar to PV systems, wind turbines also convert the intermittent renewable energy of wind into electricity. As the turbine rotates in the wind, the generator is driven to produce electricity. A single wind turbine can range in size from a few kW to more than 5MW with an average capacity factor of 20%-40% [w4]. For large scale applications, a group of wind turbines are placed in the same location and connected to the transmission system, appearing as a wind farm. Although residential systems (5-15 kW) are available, they are generally not suitable for urban or suburban homes due to large space requirements and people's perception of wind turbines in the landscape.

The intermittency and the non-dispatchable nature of both solar energy and wind energy production are the main disadvantages for these technologies. For Electrical grids without sufficient fast reserve, these drawbacks can have significant impacts on system stability. Therefore, storage solutions and load management techniques such as load shedding are normally used to even out the power production of PV systems and wind turbines when their penetration level in a system is relatively high.

2.1.4 Active demand

Active demand refers to a wide range of demand side appliances such as freezers, air conditioners and electric heaters, etc. These appliances can respond to the corresponding requests to adjust their consumption levels in order to provide valuable services like fast reserve or to attain cost-effective solutions for demand side management. The requests are sent either implicitly (as incentives) or explicitly (as control signals). For the former case, the communication between the central management system and individual appliance is necessary while the latter may not need communication as the control signals can be sensed locally such as system frequency.

Today, examples of using active demand to meet predefined objectives are well known in many places. In the US Olympic Peninsula project [r5], 112 homes are equipped with energy-management systems which provide a user-programmable automatic demand response capability for residential water heater, thermostatically controlled **H**eating, **V**entilation and **A**ir **C**onditioning (HVAC) systems, allowing these demands to bid in the local power market and react to the 5 minute market clearing price. Peak load reduction, as one of many objectives of this project, is successfully achieved. Likewise, the Danish **D**emand as **F**requency controlled **R**eserve (DFR) project has activated a great number of electric heaters, etc. via locally sensed frequency signals to provide fast reserve [r6]. This application makes great contribution to meet the ambitious goal of the Danish government: achieving 50% percent wind power penetration in the Danish power system [r7].

2.1.5 Grid-related concerns over Distributed Energy Resources integration

The development of DER technologies has shown a multitude of positive effects on power system operation; however, there exits many concerns over the increase of DER with respect to grid operation. These concerns are mainly about the electrical system security and the power quality [a3], and require proper methods to deal with them.

Concerns about system security are normally attributed to the non-dispatchable DER (like PV or Wind turbines) or partial disptachable DER (like µCHP units). When the capacity share of these resources increases to a certain level, system operators have to pursue more regulating power to assure the system security as a last resort. Furthermore, with the possibility of encountering bidirectional power flow, the conventional protection schemes are being challenged. Meanwhile, as most DER are not connected to the **S**upervisory **C**ontrol **A**nd **D**ata **A**cquisition (SCADA) systems and work in the “fit and forget” way, it becomes very difficult for the system operators to monitor and control DER with respect to the overall system security or efficiency.

Power quality concerns about transient voltage variations and harmonic distortions are also very common. For instance, on the one hand, the operation of DER can result in significant influence on the local voltage level without appropriate voltage control schemes; on the other hand, DER also show the odds of improving the local voltage quality with careful design [a10].

2.1.6 Market-related concerns over Distributed Energy Resources integration

At present, most of the connected DER are subsidized by the incentive schemes. In order to support the growth of DER penetration, it is commonly agreed that a commercial environment would extract corresponding benefits associated with increased amount of DER [a3]. However, the current electricity markets have significant barriers for the market entries of DER.

In today’s Nordic marketplace, minimum bid size requirements are defined for all markets in order to reduce the burden on communication and computation. In Elspot (day-ahead wholesale market), the minimum contract size is 0.1 MWh/h, while in Elbas (intra-day wholesale market), at least 1MWh/h is required to contract in [a11]. As for regulating power market, the minimum volume is 10MWh/h except in Norway, where 25MWh/h is normally used [a56][r9]. These capacity requirements have recently become the biggest hurdles for the DER market participation, since rare DER technology can break such bottleneck alone.

2.2 Smart metering, Home Energy Management System and prosumer

One of the most distinguishing features of future electricity grid will be users' ability to be actively involved in energy supply. For those end users who have DER installed at their premises, a new identity named Energy "Prosumer" is given to them to highlight their activeness in both producing and consuming. However, to achieve and maintain this activeness, smart metering and HEMS have to be applied in the first place.

At present, there is no single definition of smart metering, however all smart meter systems may look like what is depicted in **Figure 2-3**. At its most basic, the smart meter provides the **A**utomated **M**etered **R**eading (AMR) with respect to electricity/gas/heat/water consumption/generation at customer premises [b3]. Such application provides the utilities with real-time information of the demand side. **A**utomatic **M**eter **M**anagement (AMM) or **A**dvance **M**etering **I**nfrastructure (AMI) extends AMR with the ability to remotely measure detailed, time-based information and transmit such information to various parties after appropriate data management. For the customers, all the measured data is visualized to the customers at their computers through the **H**ome **A**rea **N**etwork (HAN), which could be formed based on different communication technologies such as **P**ower **L**ine **C**arrier (PLC), wireless technologies (Zigbee, GSM/GPRS) or existing internet connections (ADSL), etc. The customers are therefore able to view how much energy they are consuming/producing and how much it is costing/making, and take appropriate reactions.

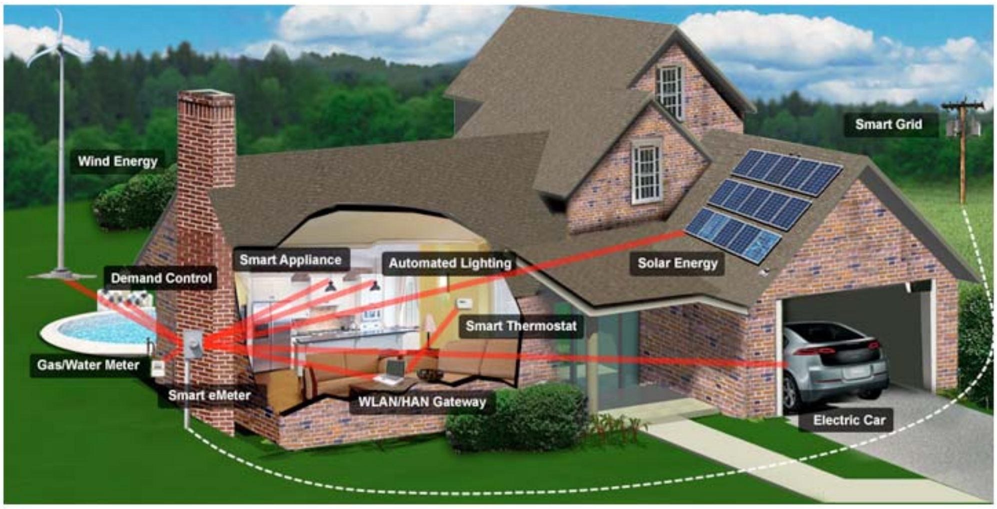

Figure 2-3: Smart meter deployed at a house

Generally, the data collected by smart meter is fed to an onsite HEMS that locally optimizes energy generation/consumption on the premises. The HEMS can be interpreted as a substitute of the customer which continuously makes optimized energy generation/consumption strategy based on a series of information including price information, the comfort level and the local generation/consumption portfolio, etc. It includes both software and hardware components (PLC, RTU, PC, thermostats, etc.) to control different home energy appliances, from consumption to generation, in order to achieve the best use of available resources without compromising the comfort level of the customers. In **Figure 2-4,** the HEMS developed by Control4 [w5] is shown. Using this system, the customers can intuitively see how much energy they are using. Control actions can be activated either by the customers or the system itself. In this case, the house depicted in **Figure 2-3** turns into a mini-VPP alike system.

Figure 2-4: HEMS developed by Control4

Taking advantage of the linkage formed by smart metering and HEMS between the customers and their onsite energy devices, integrating the domestic prosumers into the electricity system becomes achievable. Previous passive customers can now become smart prosumers and benefit from their active participations in the operation of the electricity system via VPP-like frameworks.

2.3 State of the art of Virtual Power Plant

Using aggregation to achieve better use of available generation/consumption resources is not a new technology. Many energy trading companies have already been aggregating small (from hundreds of kW to several MW) sized power plants for years. Normally, the intention of such aggregation is to break the capacity threshold for electricity market entry and benefits the owners of small generators and the energy traders. Besides, load aggregation is also very common to see by which individual energy users are banded together in an alliance to secure more competitive prices or to provide demand response services. The concept of a wind farm is another example of aggregation that leads to extra benefits such as more generation capacity, incurring smoothing effect, etc.[b4]

By far, there has been no consensus on the definition of the VPP. Literally, the VPP can be interpreted as a power plant with geographically located generation assets which are interconnected through the “virtually” existing communication channels. This literal interpretation happens to provide the three most basic features of the VPP: a power plant like entity/system, managing a cluster of generation assets and using advanced ICT technologies. The first feature, power plant like entity/system describes the obligations that a VPP has to fulfill and its role in the power system operation. The second feature, managing a cluster of generation assets, distinguishes the VPP from a conventional power plant by highlighting the control needs of the VPP. The third feature, "virtual", emphasizes the importance of communication in the VPP applications. As a result, the author would like to say any system having all of the three features can be regarded as a VPP.

In this study, the VPP is defined as an entity/**E**nergy **M**anagement **S**ystem (EMS) that aggregates multi-fuel, multi-location and possibly multi-owned DER units via advanced ICT infrastructure either for the purpose of energy trading or to provide system support services. Differing from other aggregations, VPP exploits the technical and economic synergies between diversified DER technologies. In the case of being an independent entity, the VPP can either function as an independent power producer (based on DER aggregation) or an energy supplier (based on prosumer aggregation). In the case that the VPP functions as an EMS, it turns into a software based application which can be used by any parties.

Due to the high flexibility of the concept itself, there exists a variety of designs and implementations for VPP. As shown in **Table 2-3** , these designs and implementations can be mainly classified by four key characteristics of VPP: aggregation needs, role of VPP, communication and control methods. Each category is explained in the following.

Table 2-3: Different VPP categories

Aggregation needs	Role of VPP	Control	Communication
Commercial ⇕ Technical	Controller ⇕ Information Agent	Structure ⇕ Strategy	Media ⇕ Direction

Aggregation needs, defines the tasks that have to be fulfilled by VPP aggregation, and can be classified into two categories: **C**ommercial VPP (CVPP) and **T**echnical VPP (TVPP). CVPP aggregates the DER in order to perform market related activities, such as energy trading in different markets from forward to spot, which aims to maximize the profit margins for the aggregated generation portfolio. For TVPP, the aggregation is normally directed to provide specific power system support services, which are essential in maintaining power quality, reliability and security of the grid. Sometimes, local network constraints and real-time local network status are also included in the VPP portfolio to assure the flawless grid operation.

Role of VPP, states the VPP responsibilities, and has a high correlation with how the aggregation could be done. When VPP functions as a central controller, the attached DER devices are operated according to the VPP's needs so as to help balance supply and demand, or to benefit from selling excessive electricity. Fast and reliable communication channels therefore have to be established in order to fulfill the communication requirements; meanwhile the VPP has to have many sophisticated functions to achieve cost-effective operation. On the contrary, VPP can also function as an information agent who might be only in charge of information transfer between DER owners and other players involved in power system operation or market transactions [a12][a13].

Control, the item used in VPP related studies normally covers two aspects: Control structure and Control strategies.

- Control structures, as depicted in **Figure 2-5**, state how the decision making is carried out from centralization to decentralization [a14]. In the former case, all decisions in the VPP are made by VPP central controller; while the latter case disperses decision-making governance closer to the DER devices. Since the intelligence level of the VPP with centralized control structure is limited by resources for calculation, communication and system redundancy, etc, decentralized control structure is favored more in handling complicated tasks. For the VPP with a completely decentralized control structure, it might turn into an information agent as mentioned before, and all the decision makings are made by DER themselves.

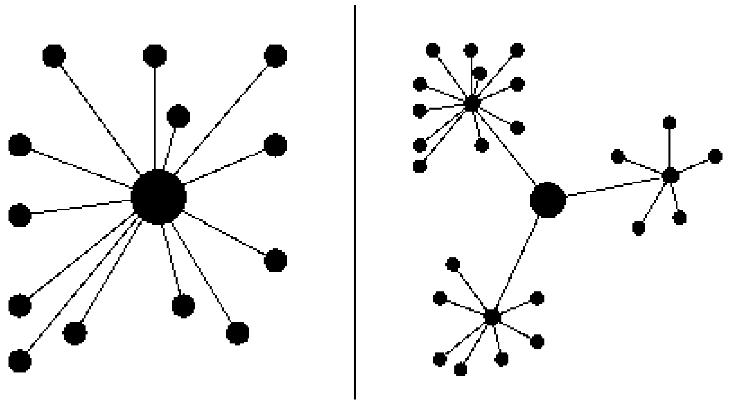

Figure 2-5: Centralization vs. Decentralization

- Control strategies, related to VPP studies are mainly with market-based control [a12][a15], agent-based control[a16][a17][a18], optimal control[a19][a20][a21], etc. Market-based control bears emphasis on creating a competitive market environment for DER devices and regulating the production/consumption of DER with market signals in order to meet the perspectives on cost and effectiveness; while agent technology highlights the importance of local intelligence of DER as well as the fast and reliable communications among the agents. The optimal control deals with the problem of finding a control law for a given system portfolio and forms the basis of other control strategies by providing mature mathematical theories and detailed optimization algorithms. Any of the control strategies can be implemented under different control structures and therefore results in a diversified flexible portfolio of VPP study.

Communication, as another key part in VPP related studies, covers a diversified communication technology portfolio [b3]. Key technologies applied in VPP-like applications include Internet based technologies e.g. the **I**nternet **P**rotocol (IP) based services through public broadband access, **V**irtual **P**rivate **N**etwork (VPN), PLC and wireless technologies e.g. GSM/GPRS, 3G, etc. Within customer premises, WiFi, Bluetooth, Zigbee, etc. are utilized to form the communication network. In general, VPP and DER communicate with each other in either one-way communication or two-way communication. The cost of a one-way communication system is usually cheaper than a fast and reliable two-way communication system. However, as only inquiry or broadcast is applied in the former system, the VPP lacks assurance of the DER response, either before or after issuing the control signals. State estimation is therefore a must in the VPP with one-way communication systems.

In **Table 2-4,** recent projects or ideas regarding VPP are summarized, following with general information. Detailed descriptions are given in Appendix C.

Table 2-4: Review of VPP technologies

VPP projects	Aggregation needs	Role of VPP	Control Methods	Communication
EUVPP [r8], a demonstration project of VPP concept in 2005, which aggregated 29 decentralized fuel cell based µCHP units	Technical needs: ▪ Peak load reduction ▪ To follow pre-defined load profiles	Central controller	Centralized control	two-way communication: internet VPN tunnel one-way communication: RRC
VPPs based on the idea of Power Matcher[a16],[a22], which applies multi-agent based control on DER side	Technical needs: ▪ Peak load reduction, etc.	Agent broadcasting electricity price	Decentralized market-based control	Two way communication: **U**niversal **M**obile **T**elecommunication **S**ystem (UMTS) wireless network
	Commercial needs: ▪ Bid in electricity spot market	Market operator of internal market; Market player in external electricity market		
FENIX VPP [w6], a demonstration project of large scale VPP concept in Europe	Technical needs: ▪ Provide Tertiary Reserve ▪ Provide Voltage control services ▪ Solve Network Contingencies	Central controller	Centralized control	Two way communication: GPRS and IEC-104 protocol.
	Commercial needs: ▪ Participate in the day-ahead electricity market. ▪ Access ancillary service market	Market operator of internal market; Market player in external electricity market	Decentralized market-based control	
Edison VPP[w7], a demonstration project of VPP concept specializing on Electric Vehicles(EV) integration	Technical needs: ▪ Provide possible balancing services to Gid ▪ Provide cost-effective control over EV fleet	Central controller	Centralized market-based control	Two way communication based on IEC61850
ProViPP [w8], a demonstration project based on Siemens' DEMS, which aggregates 9 hydroelectric plants 86 MW	Commercial needs: ▪ Participate in the electricity market ▪ Participate in the reserve market	Central controller	Centralized market-based control	Two way wireless communication

2.4 Summary and discussions

In this chapter, several key components e.g. DER, smart metering and HEMS of the VPP are shortly reviewed at the beginning. Compared with conventional generation technologies deployed in today's power system, DER posses the capability of "reinventing" the grid if their perceived benefits, such as lower emission, higher reliability, etc, can be fully realized. However, inappropriate "fit and forget" deployment approach of DER has also raised many concerns over system operation and market participation, which must be addressed by more advanced control/coordination schemes. Counted as the basic supporting devices, smart meters and HEMS create the foundation for developing the future intelligent system framework, through which each house can function as a mini-VPP. Control/coordination schemes can be implemented both locally and globally to strengthen the upsides of DER. As an enabling concept, the VPP aims to establish such kind of control/coordination framework to support the integration of DER.

The VPP studied in this research project is a specific kind of VPP, for which the generation assets to be coordinated inside are DER. Still, being a very broad concept, the aggregation technologies used in this VPP exhibit quite different feature when they intend to address the questions: why to aggregate, what to be aggregated and how the aggregation is implemented. According to the real life experience, there seems no technical hurdles for aggregating tens of DER units with centralized control scheme as long as the computation and communication barrier can be well handled by the ICT technology. Further, from the utility's point of view, a fully centralized control allows for them to make little change to the existing operation schemes and tariff structures. When the number of VPP participants becomes dramatically large, decentralized control seems necessary. Fully decentralized control architecture may be able to solve the computation and communication overhead as the decision making processes are distributed down to DER level; however the unlearned issues such as instability and unpredictability leads to other anxieties. In the light of today's DER penetration level, many VPP technologies are mainly employed with centralized structures; while some decision capabilities are granted to DER systems in the meanwhile to ensure a certain level of adaptability.

Among most VPP designs, market participation seems to be one of the primary tasks. Reasons for this can be attributed to,

- The profitable market-based operation represents the ultimate needs for VPP aggregation in a deregulated power system
- Its efficiency in coordinating different resources
- Its openness to all DER technologies
- Potential economic benefits for the DER owners and other market participants

As the key part of VPP concept, many different communication technologies have been selected and tested in recent studies. Finding out the best communication solution for VPP technologies is not an easy task and out of the scope of this thesis. But it is well believed that the communication infrastructure of VPP must provide high level of scalability, stability and flexibility, also trying to use ‘every’ already existing communication resources.

3 DEVELOPING MARKET-BASED VIRTUAL POWER PLANT

The present deregulated electricity markets encourage the competition in both generation and demand sectors to achieve socio-economic efficiency and freedom of choice for the customers. Market for ancillary services, which are used to maintain reliable operations of power system, further provides a trade route connecting power system operators and a group of **Gen**eration **co**mpanie**s** (Gencos) or customers who are able to provide dedicated services. In light of this, this chapter aims to address the research question "how to develop a generic VPP concept which benefits all parties" by presenting a detailed design of **M**arket-**B**ased **VPP** (MBVPP) operation scheme. In section 3.1, the Nordic power market is introduced. In section 3.2 and 3.3, within the framework of the Nordic power market, the architecture of the MBVPP system and different control strategies are presented respectively. Section 3.4 presents a function-based design for the MBVPP and Section 3.5 summarizes the study given in this chapter.

3.1 Nordic power market

In 1990s, Norway, Sweden, Finland and Denmark instituted stepwise opening of their national power markets on the heels of each other, as shown in **Figure 3-1**. This sluggish reform has successfully created a new competitive multinational environment for power trading, and serves as a model for restructuring other power markets.

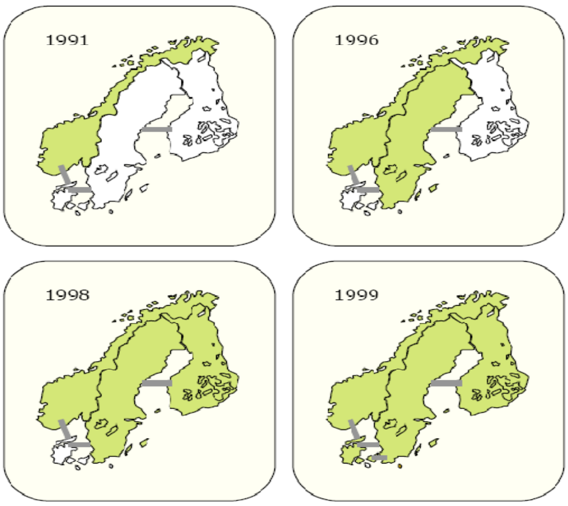

Figure 3-1: Development of the deregulated Nordic Power Market

3.1.1 Current marketplace of Nordic power system

Today, the Nordic Power Market is well-known for its high liquidity and its efficient market functions. **Figure 3-2** illustrates the major components of this market.

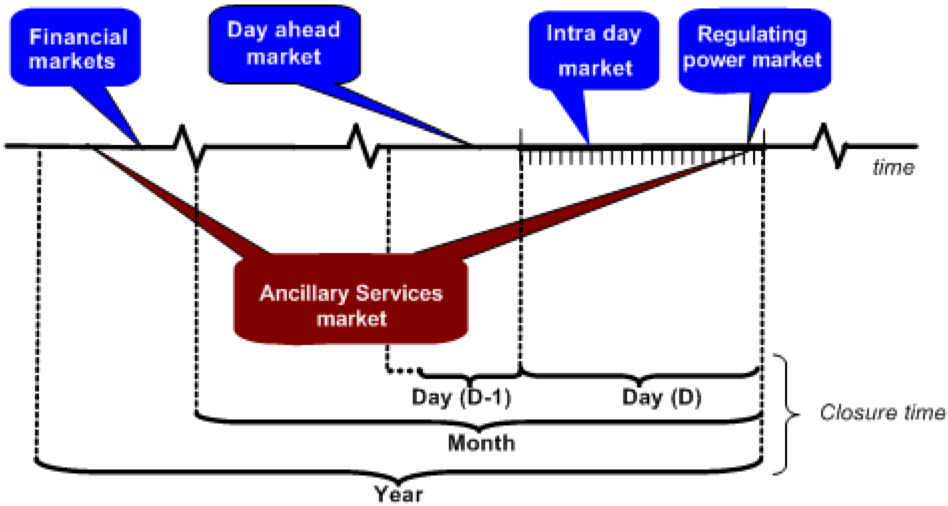

Figure 3-2: Timeframe for different market services in Nordic Power Market

The financial market for price hedging and risk managements consists markets for futures, forwards, options, etc., which deal with the kinds of contracts that are agreed from months or years before they get executed. The day-ahead market, so called Elspot, provides the market participants a place where hourly power contracts are traded daily for physical delivery in the next day's 24 hour period. Elbas kicks in as an alternative of balancing market and provides continuous power trading up to one hour prior to delivery. The regulating power market, run by the Nordic **T**ransmission **S**ystem **O**perators (TSOs), provides the tool to keep the real-time balance between total generation and consumption of power. Furthermore, ancillary services, including frequency reserve, voltage support, etc., can be traded from long term to short term in the TSOs organized markets.

A simple sk,etch of the current marketplace for Nordic power system is given in **Figure 3-3.** Most of the electrical energy is generated by conventional generation technologies, and transferred down to end users through transmission and distribution systems. Large DG groups, such as windfarms, CHPs, etc., which are connected to MV distribution system, might have direct access to the power market. The customers with installations of DER have turned into sort of prosumers, who can also produce electricity rather than consume it only. The reversed energy flow between distribution system and transmission system is rarely observed due to the relatively low penetration level of DG&DER; however, this might happen in the near future if the penetration level continues to rise.

Compared to electric energy flow, the information flow is more complicated. The information exchanged between the market players and the market coordinator may include bids and offers as well as the relevant market information; while the information exchanged between energy suppliers and end-users includes metered data (monthly-based without AMI) and pre-defined electricity tariff for end-users with/without DER respectively. In terms of the money flow, Gencos, large DGs and end-users with DER are the only parties receiving money from selling the electricity. However, the first two groups receive money from market participation and the last group receives money based on governmental incentives such as net metering, feed-in tariff, etc., and therefore functions in ways like “fit and forget”. It is worth mentioning that TSOs and DSOs are obligated to maintaining the system security for transmission and distribution system respectively and mainly deal with ancillary services transactions.

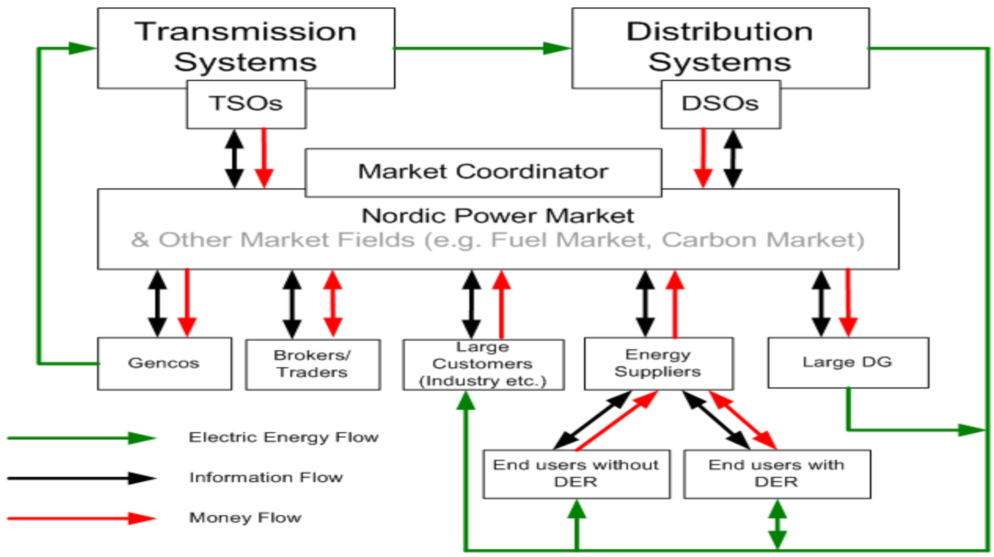

Figure 3-3: Current marketplace in Nordic Power System

3.1.2 Balance regulation of the Nordic power system

Maintaining the constant balance between generation and consumption is the key process in any power system operation. The Nordic power system use market-based mechanism to procure various types of regulating resources and peak load resources, as show in **Figure 3-4**, to meet this requirement in the synchronous part of Nordel and another balance area-western Denmark, which belongs to UCTE system. The frequency controlled reserves can be obtained by TSOs from the ancillary service market and are activated automatically by frequency deviations under different conditions:

1) Normal operation reserve, with total amount of 600MW and regulation capacity of 6000MW/Hz, is fully activated at a frequency of 49.9Hz.
2) Disturbance reserve, often around 1000MW, is activated when frequency drops down to 49.5Hz when situation like loss of a large power plant is encountered.

The fast reserves can be bought from the regulating power market mentioned before. They are activated manually and used to restore different types of the automatic reserves within 15 minutes. Peak load agreements are sort of a type of ancillary services, which are designed to handle peak load situations when fast reserves prove insufficient.

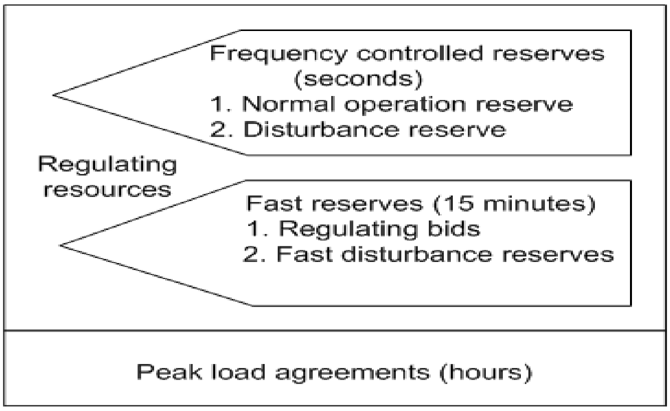

Figure 3-4: Balancing resources in Nordic power system

Through three basic steps: planning, regulation and settlement, the TSOs are able to coordinate different balancing resources to ensure physical balance and safe system operation.

It is worth mentioning that this section briefly summarizes the important features of common balance regulation. There still exist national differences. For detailed knowledge, the readers are recommended to go to the individual TSO website or visit the website of Nordel [w9]. For the VPP which aims to provide specific balancing services, the corresponding regulation code has to be met.

3.1.3 Electricity market prices

Current electricity prices in the Nordic power system, especially in Denmark, are relatively volatile due to the fact that there is a high penetration of wind power in Denmark. Although studies show that the spot prices in Denmark were reduced by 0.25-0.45 c€/kWh in 2005-2007 [a23], as seen in **Figure 3-5**, electricity price spikes can be often observed in both spot market and regulating market. These high price spikes obviously indicate the need of additional generation or demand resources for those hours, and provide the potential business fields for the new entities like the VPP. Economically, if DER technologies like µCHP can participate in the electricity market through the VPP, the DER owners can receive an extra amount of savings in contrast to the current fixed buy-back prices [a24]. Meanwhile, the corresponding reactions from the DER owners can mitigate the problems caused by electricity shortage or excess.

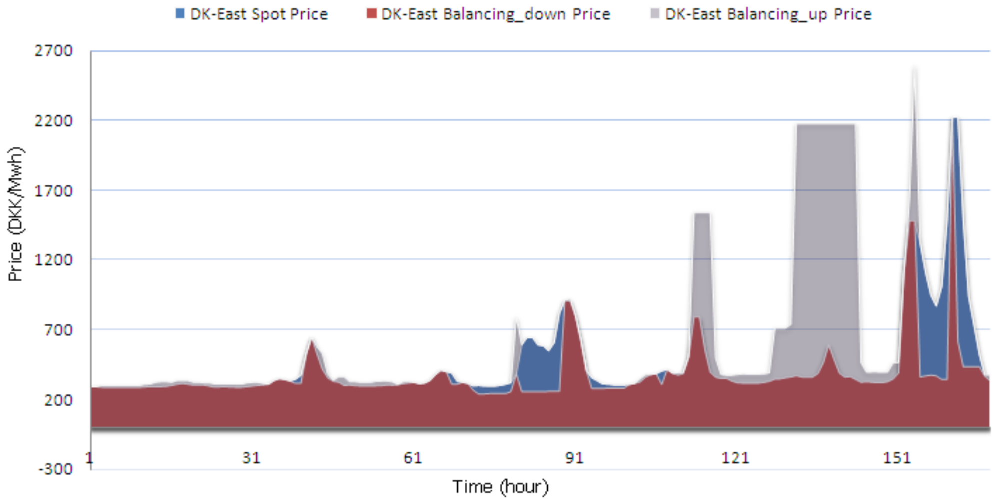

Figure 3-5: Electricity market prices for DK-East in the 1st week of 2010 (Source Energinet.dk)

3.2 System architecture design for market-based Virtual Power Plant

The MBVPP is a kind of VPP that plays actively in the existing electricity market by buying/selling electricity or grid-related services from/to the other market players. The phrase "market-based" aims to distinguish the MBVPP from the others by emphasizing that the decisions carried out by the MBVPP are based on market signals.

As illustrated in **Figure 3-6**, the MBVPP breaks the size limitation for market participation by aggregating adequate number of prosumers with DER installed at their premises. The assets of these prosumers are further split into two groups: passive load (lighting load, etc.) and DER, implying the MBPP has the option to aggregate either DER only or the entire premises. In the former case, the passive load within the premises could be met by energy suppliers, like other end users who don't have DER facilities; thus the MBVPP acts as an independent power producer. In the latter case, the MBVPP could both generate and consume electricity, which appears like an energy supplier equipped with its own generation facilities. Taking advantage of the diversified DER technologies, the MBVPP represents a very flexible generation portfolio and therefore has the possibilities to trade both electrical energy and different kinds of ancillary services.

There also exits the possibility that the MBVPP turns into a software based EMS. In such case, the MBVPP is dedicated to managing DER facilities. It is used by the energy suppliers to ensure reliable energy supply to the end-user and to provide grid-supportive services.

Being a relative large party in the market field, the MBVPP can also intervene in other business fields such as fuel markets and carbon markets. The participants in the MBVPP may thus obtain further benefits e.g. cheaper fuel prices.

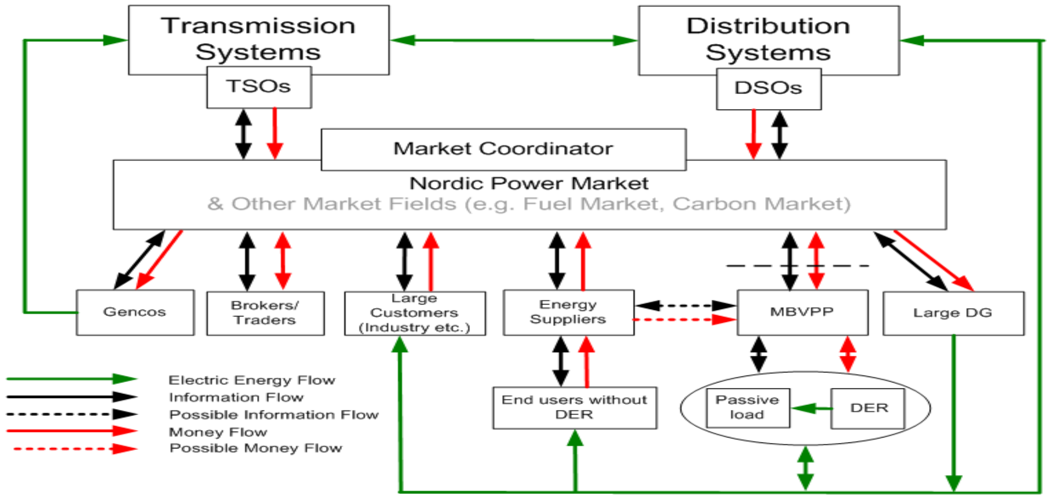

Figure 3-6: Marketplace in Nordic Power System with MBVPP

In detail, **Figure 3-7** illustrates the physical topology of the MBVPP, including the energy flow, communication flow and the physical components. All the control/coordination functions reside on the central server, while the energy management system is carried by the client server like the HEMS. Information flow between the central server and client server is maintained in the predefined time frequency, in order to complete the overall control/coordination process. In case that the communication/computation bottleneck occurs, sub servers can be equipped to distribute the work load which forms a hierarchical system structure. However, the variations led by different control strategies will result in different kinds of MBVPP which will be explained in next section.

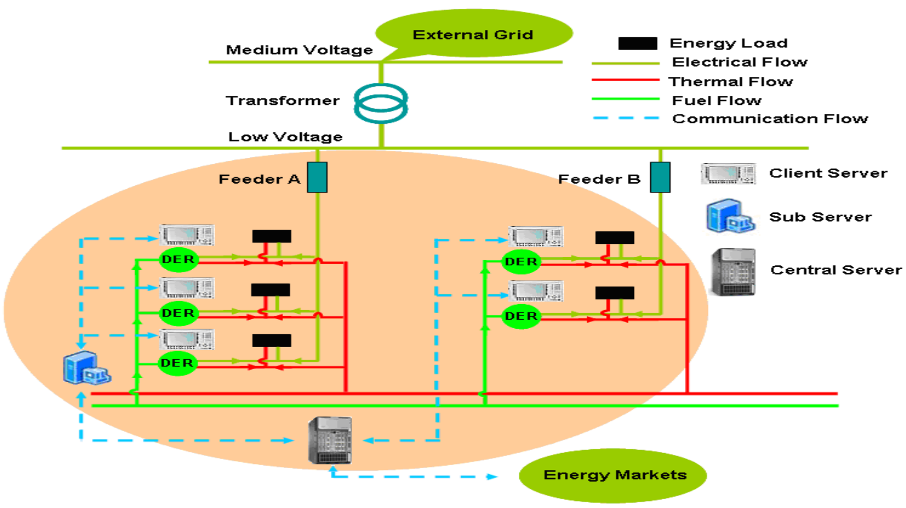

Figure 3-7: Physical Topology of the MBVPP

3.3 Different control schemes of market-based Virtual Power Plant

Depending on how the control structure is designed, the operation of the MBVPP can be carried out in several ways as depicted in **Figure 3-8**: Direct Control, Price Signal Control and Internal Exchange. These three types of MBVPP reflect how the DER intelligence and MBVPP intelligence can be coordinated differently in order to achieve the best usage of DER under different conditions or regulatory frameworks. (Here, the intelligence is interpreted as the capability of handling different levels of complexity related to decision makings.). With no exceptions, these three types of MBVPP all act as interfaces which grant the DER opportunities to get access to the electricity market.

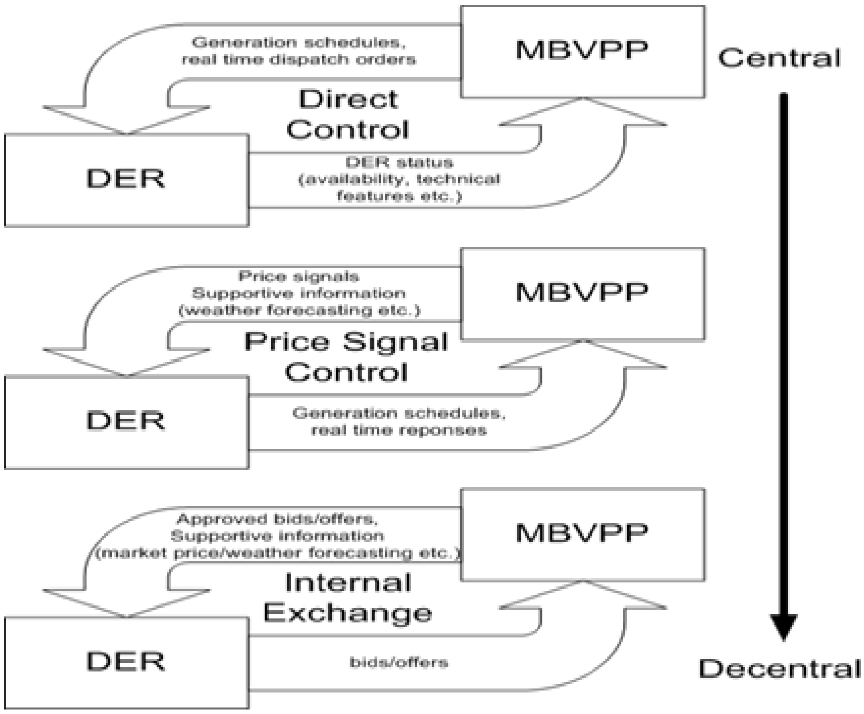

Figure 3-8: Different control schemes of MBVPP

Direct Controlled MBVPP: Under this scheme, the MBVPP has the direct access to control all DER in the case of extremely centralized control structure is applied. To better operate the aggregated DER portfolio, the MBVPP normally requires the complete knowledge over the generation characteristic and the corresponding locational information, etc. For a standard energy transaction taken place in the electricity market like day-ahead market, the MBVPP will generate and submit its bids/offers based on the already known generation portfolio. The approved bids/offers therefore will be transformed to the generation/consumption schedules for every DER. When real-time comes, the MBVPP dispatch the DER to mitigate the imbalances caused by forecasting errors or emergencies. As all the decision makings are made by the MBVPP, a relatively high intelligence level is required to optimize the overall operation.

Price Signal Controlled MBVPP: By broadcasting price signals to the DER, the MBVPP can regulate the operation of the DER to some extent [a12]. For instance, broadcasting the hourly electricity price for tomorrow may modify the DER generation schedule and lead to efficient energy usage; broadcasting a five minute electricity price for the next five minute may help to collect enough balancing power for the MBVPP. However, how well this scheme can function depends on a lot of variables. As the MBVPP normally has to deliver the committed energy or services, it has to find out the generation/consumption pattern of the mixed DER generation portfolio according to different price signals and develops efficient varying pricing signals to invoke the reactions. Further, the stochastic generation patterns caused by irrational human decisions or the increasing local intelligence may cause more complexity to design the price signal controlled scheme. However, the simplicity of broadcasting price signal is the biggest advantage of this strategy.

Internal Exchange based MBVPP: the MBVPP working with this strategy needs the lowest intelligence requirement among the three presented types of the MBVPP [a12]. Instead of carrying out control functions, the MBVPP here only has to operate an internal exchange electricity market and deliver supportive information to the DER. Based on these information, the bids/offers are made by DER and submitted to the internal market. The bids and offers can be either cleared or aggregated internally. The aggregated bids/offers will be sent to the external electricity market for clearance. The approved bids and offers will turn into generation/consumption schedules of the DER. In real-time, the DER has to follow the schedule in order to minimize the penalty cost caused by imbalances.

3.4 Functional requirements of market-based Virtual Power Plant

The functional requirements for different types of MBVPP vary from each other; however, it is possible to use function-based design to find the universal functional modules of the MBVPP as give in **Figure 3-9**. In the case of developing a specific type of MBVPP, these functional modules can be easily selected to build a complete MBVPP system. In [a25] which is also attached to Appendix D, detailed description of each functional module is given.

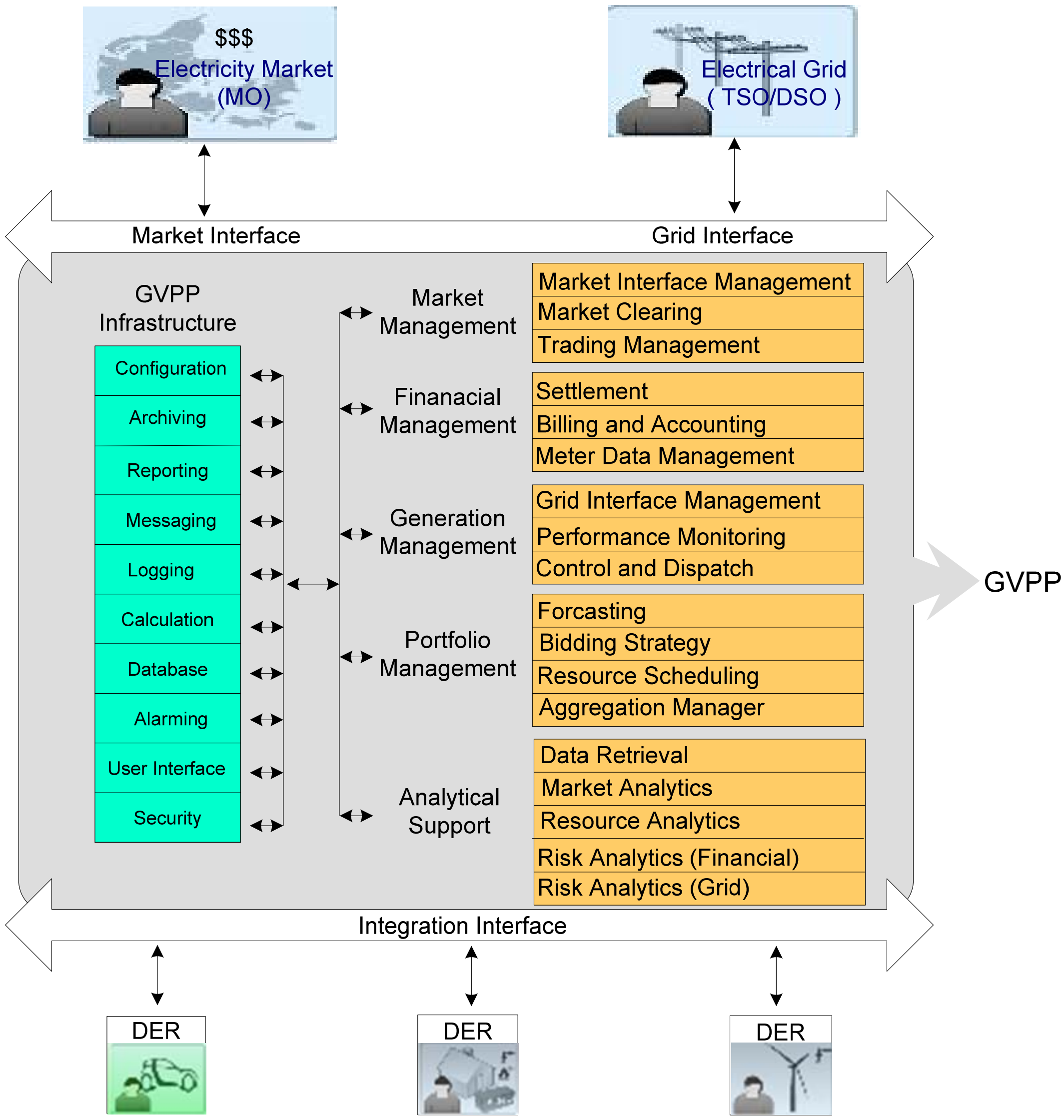

Figure 3-9: Universal functional modules of the MBVPP

To illustrate the utilization of the proposed function-based design, an example of price signal controlled MBVPP system is constructed on basis of the proposed functional modules, details of which is given in [a25]. In **Figure 3-10**, the information diagram for this VPP is shown. Day-ahead trading is carried out following the direction of the hollow arrow which starts from the analytical module and ends with the generation schedule. In real-time, the price signal control algorithm is implemented as a closed loop control, aiming at making the real-time generation comply with the schedule. Communication between DSO and the MBVPP is maintained if needed.

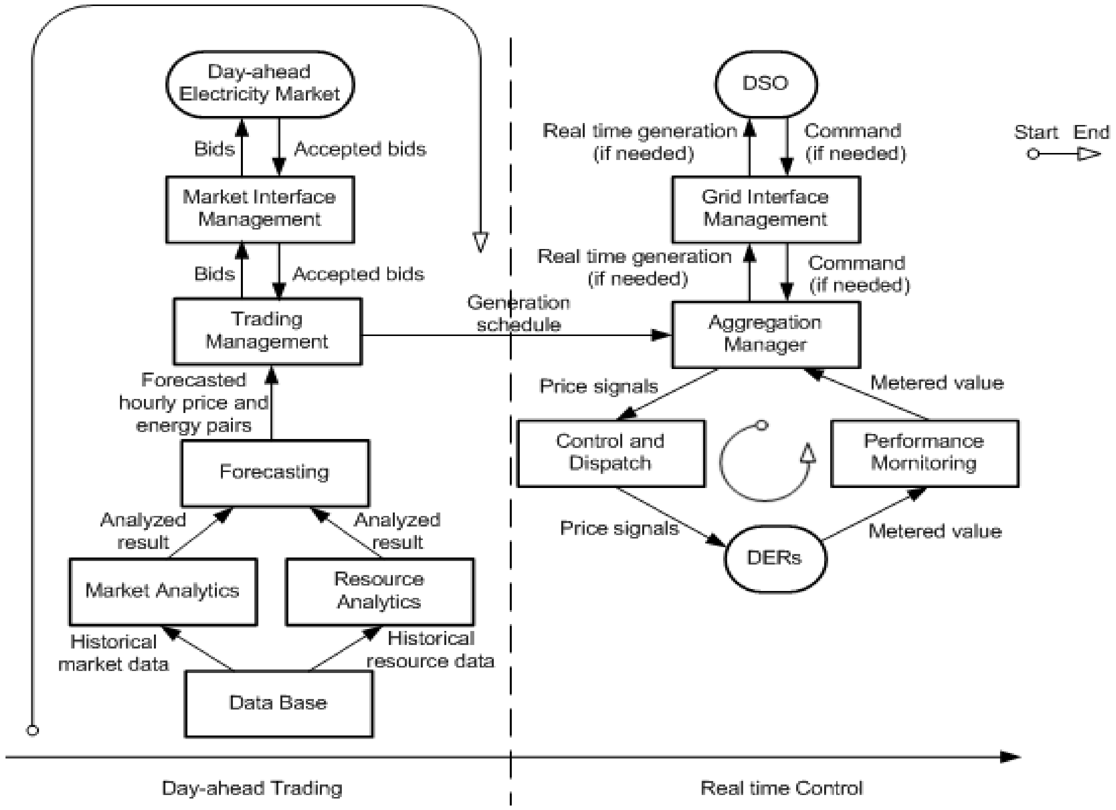

Figure 3-10: Working flow of the price signal controlled MBVPP

3.5 Summary and discussions

Market-based control is always conventionally taken as one of the best ways for distributed resource allocation. The MBVPP developed in this chapter can be easily fit into today's electricity marketplace of the Nordic power system, thus establish a bridge between the DER and other existing market players. The volatility of electricity market prices and the variety of market products provide the MBVPP with great market potential.

Even though the architecture for the MBVPP is very clear-cut, the MBVPP can still be implemented in various ways such as direct controlled, price signal controlled and internal exchange based operation. They differ from each other in terms of the decision making principles and the incurred information flows. The first two types of MBVPP generally require complicated decision makings in order to obtain optimized generation and trading portfolios. Therefore, they are modeled and simulated in the next two chapters. As for the MBVPP which operates internal exchange markets to coordinate the DER production, it can be regarded as a copy of today's wholesale market and the MBVPP is no other than a market operator. It therefore has more concerns about the efficient market design and how it can be coordinated to the existing electricity market. Further, since submitting bids and offers by prosumers can be very burdensome and may discourage their participation, this idea is not studied in the later sections of this thesis.

For all the MBVPP, there is a list of generic function requirements covering their needs on managing the DER, accessing the existing power markets and cooperating with other parties in the electricity sector. The flexibility brought by the function-based design can therefore facilitate the design of MBVPP when different needs have to be met. (In the following, for the sake of simplicity, the term "VPP" is used instead of "MBVPP" due to the fact that the market-based operation is considered as a necessity of all VPP related activities in this study.)

4 DIRECT CONTROLLED VIRTUAL POWER PLANT

Any power plant in a deregulated market environment are now exposed to risk and uncertainties coming from different sectors, such as the technical limitations imposed by the power plant itself, the volatile electricity market prices, fuel price uncertainty, etc. Therefore, to optimize the generation and trading portfolio of a power plant can be in principle taken as a decision making problem. From this point of view, the only distinction between operating a VPP and operating a conventional power plan might be the amount of information that is available to the power plant operator.

For a direct controlled VPP, it normally requires the VPP to have adequate information over every DER participant and the corresponding locational context. Such framework not only helps the VPP to precisely characterize its generation portfolio that improves market-based decision makings, but also allows the VPP to more accurately regulate its generation in real-time as the VPP operator has direct access to the control panel of every DER participants.

In this chapter, instead of including a diversified DER portfolio, the µCHP system is modeled and simulated in section 4.1. In section 4.2, the optimized operation a µCHP formed direct controlled VPP under present deregulated market conditions is modeled. A case study for a VPP with 10 µCHP systems is presented in Section 4.3, and the result reveals that when adequate information about the DER and the electricity market are available, the direct controlled VPP can optimize its generation and trading portfolios to achieve the overall cost-effective operation. Section 4.4 summarizes and discusses the finds of this study.

4.1 Modeling least cost controlled micro-combined heat and power system

The µCHP systems, which have been introduced in 2.1.1, are currently on the verge of massively replacing the conventional domestic heating systems. According to [w10] published by Delta Energy & Environment, around 20 thousand µCHP systems[4] with the electrical capacity of 37.8MW have been sold worldwide. In addition, unlike the

[4] Delta defines µCHP as generating 5kW of electricity or less.

wind turbines and PVs which have intermittent generation characteristics in nature, the power output of µCHP systems can normally be precisely controlled. The two advantages of the µCHP systems: market potential and controllability make them more preferred by the VPP operators.

A substantial body of literature exists describing the models, control strategies and the associated economic performance for µCHP systems based on different prime mover technologies. In [a26][a27][a28][a29], the three operation strategies: heat-led, electricity-led and cost-led which can be generally applied to any kind of µCHP systems are intensively investigated. For the heat-lead operation strategy, the µCHP system is controlled to meet the onsite heat demand as much as possible and the associated electricity is considered as the by-product. On the contrary, the electricity-lead control intends to closely follow the onsite electricity demand by dispatching the unit. The cost-lead operation is generally considered as the optimized operation strategy that minimizes the cost of meeting the given electricity and heat demand profile, subject to the technical constraints of the system. In these studies, regardless of the prime mover technologies being modeled, constant power to heat ratios and overall efficiencies are generally used to describe the generation characteristic of the µCHP systems. This assumption makes the simulations easy to implement and provides reasonable estimates of annual performance.

Detailed electrical and thermal performance of the µCHP systems can be found in [a30][a31][a32], wherein the empirical models are used to simulate the performance of SE and ICE based µCHP systems in building integrated cogeneration applications. In these models, the electrical efficiency and thermal efficiency of the µCHP systems are expressed as a polynomial function of the part load ratio or thermal energy input in order to simulate the effects of incomplete combustion, friction and vibration, etc. Furthermore, the cold start behavior of an ICE is modeled as a function of operation time in [a32]. However, since these models are developed on empirical data collected for specific µCHP system, they hardly can be recalibrated for representing other cogeneration systems.

To demonstrate the optimized operation of a direct controlled VPP, a decentralize-controlled µCHP system is firstly modeled in this section.

4.1.1 Model description

The system structure for the simulated µCHP system is given in **Figure 4-1**, wherein the µCHP system marked by the gray area comprises three parts: a µCHP unit, a thermal storage and a gas-fired boiler. For the ICE based µCHP unit, a synchronous generator is driven by an ICE to produce electricity. The useful heat generated by this unit is mostly from the heat recovered from engine jacket cooling water and the exhaust gas. The gas-fired boiler is used as an alternative heat source; whilst the heat storage which is usually a hot water tank is used to further increase the flexibility of the µCHP system operation. For this grid-connected µCHP system, the generated electricity in excess of the local electrical demand could be sold back to the grid at pre-defined electricity tariffs. [5]

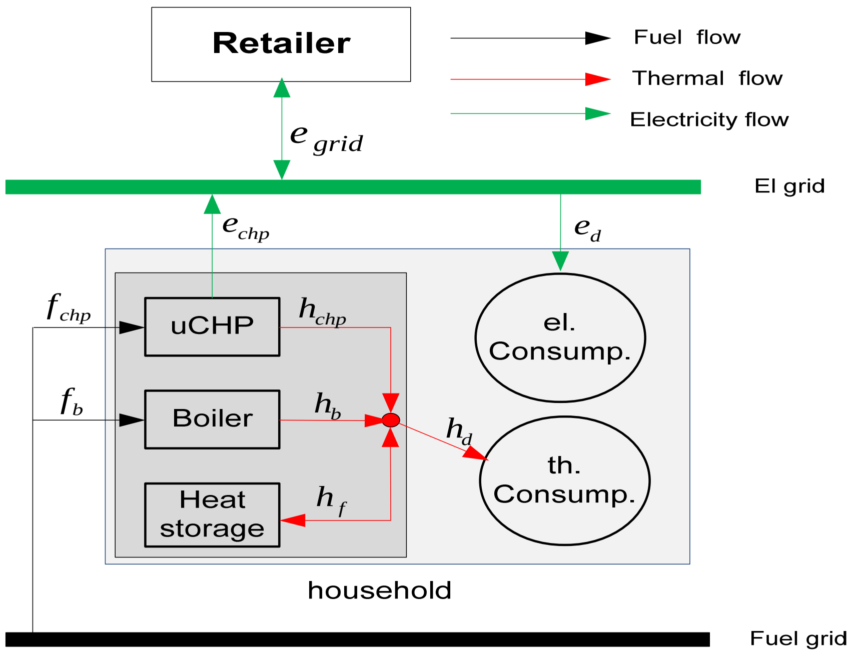

Figure 4-1: System structure for a decentralized-controlled µCHP system

For a decentralized-controlled µCHP system numbered *i*, the question about how the prosumer (the owner of the household and DER inside) can optimially operate his µCHP system to minimize his system cost can be modeled as a set of mathmatical equations. Given as following, these equations represent the technical performance of different devices and physical energy balances as well as the objective of prosumer.

With regard to the energy flow depicted in **Figure 4-1**, unit for the variables in the following energy balance equations is kWh/Δt , where Δt indicates the time length of one simulated time step such as an hour or 30 minutes. This unit is actucally equivalent to kW, meaning that within Δt a constant amount of power in kW is consumed or produced.

The heat balance and the electricity balance are given in (4.1).and (4.2) respectively.

[5] In order to promote the use of DER, there are basically two types of electricity tariffs used to remunerate the electricity produced by DER: net metering (remunerating the exported electricity) and feed-in tariff (pricing the generated electricity). Normally, the electricity price for net metering is time dependent and for feed-in tariff is constant for a given DER technology.

$$h_{chp,i}(t) + h_{b,i}(t) + h_{f,i}(t) = h_{d,i}(t) \tag{4.1}$$

$$e_{chp,i}(t) + e_{grid,i}(t) = e_{d,i}(t) \tag{4.2}$$

Where

$$e_{grid,i}(t) = \begin{cases} e_{im,i}(t) & if \quad e_{grid,i}(t) \geq 0 \\ -e_{ex,i}(t) & if \quad e_{grid,i}(t) < 0 \end{cases} \tag{4.3}$$

The thermal storage balance is modeled by a difference equation given in (4.3),

$$h_{s,i}(t) - h_{f,i}(t) = h_{s,i}(t+1) \tag{4.4}$$

And the capacity limit for all devices are modeled as following,

$$f_{chpmin,i} \leq f_{chp,i}(t) \leq f_{chpmax,i} \tag{4.5}$$

$$f_{bmin,i} \leq f_{b,i}(t) \leq f_{bmax,i} \tag{4.6}$$

$$h_{smin,i} \leq h_{s,i}(t) \leq h_{smax,i} \tag{4.7}$$

The generation characteristics for the boiler is modeld by (4.8),

$$h_{b,i}(t) = f_{b,i}(t) * \eta_{b,i} \tag{4.8}$$

The generation characteristics for the µCHP unit are modeled as following linear equations,

$$h_{chp,i}(t) = (a_{1,i} \cdot e_{chp,i}(t) + b_{1,i}) \cdot o_i(t) \tag{4.9}$$

$$f_{chp,i}(t) = (a_{2,i} \cdot e_{chp,i}(t) + b_{2,i}) \cdot o_i(t) \tag{4.10}$$

where the binary variable $o_i(t)$ is used to indicate the on (1)/off (0) status of the µCHP system

Here, the ICE-based µCHP unit XRGI15 from EC Power A/S [w11] is simulated. The electrical output of this unit can be modulated between 6kWe to 15.2kWe. As denoted by [a33], when this unit runs on natural gas (NG), the thermal output and fuel input are both in linear relationship to its electrical output when the unit is on. Thus the generation characteristics of this unit are modeled by two linear equations (4.9) and (4.10) provided the system performance described in [w11], and are depicted in **Figure 4-2**.

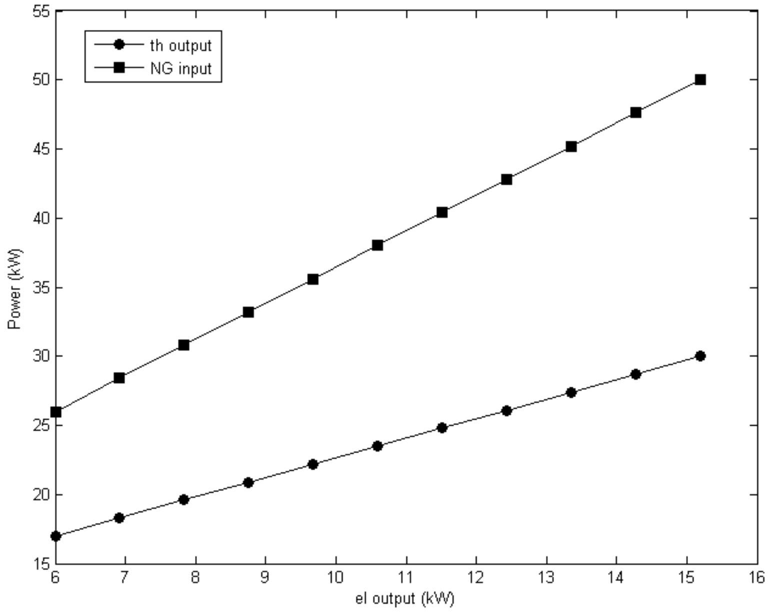

Figure 4-2: Generation characteristic of the simulated XRGI15 unit

The corresponding electrical efficiency, thermal efficiency and overall efficiency of this unit, which are expressed by (4.11), (4.12) and (4.13), can therefore be calculated and drawn in **Figure 4-3**. As a result the overall efficiency is around 90% and the maximum electrical efficiency is about 30% when the system runs at maximum output.

$$\eta_{chpel,i} = e_{chp,i}/f_{chp,i} \tag{4.11}$$
$$\eta_{chpth,i} = h_{chp,i}/f_{chp,i} \tag{4.12}$$
$$\eta_{chp,i} = \eta_{chpth,i} + \eta_{chpel,i} \tag{4.13}$$

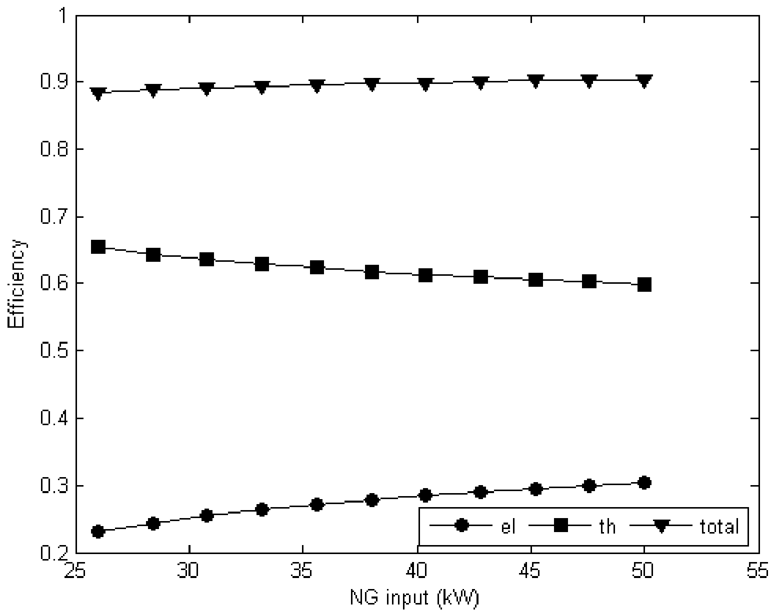

Figure 4-3: System efficiency of the simulated XRGI15 unit

The objective of such system, as in (4.14), is to minimize the total cost for one optimization period which includes T time intervals. The cost function as given in the square brackets is comprised by three parts: the fuel cost and the electricity cost caused by importing electricity from the grid and the saving due to the export of excessive electricity. Therefore, a net-metering electricity tariff is simulated in this case. Generally, if there is some heat stored in the heat tank at the beginning of the simulated period, the cost for that amount of heat also has to be included in the cost function. However, by forcing heat storage level at the end of simulated period equal to the initial storage level, as in (4.15), this cost can be eliminated in the cost function.

$$\sum_{t=1}^{T} cost_i(t) = \sum_{t=1}^{T} [\left(f_{chp,i}(t) + f_{b,i}(t)\right) \cdot \pi_f(t) + e_{im,i}(t) \cdot \pi_{im}(t) - e_{ex,i}(t) \cdot \pi_{ex}(t)] \quad \textbf{(4.14)}$$

$$h_{s,i}(0) = h_{s,i}(T) \quad \textbf{(4.15)}$$

As a result, in order to obtain the optimized operation with least system cost over a time period, one only has to solve the **M**ixed **I**nteger **P**rogramming (MIP) problem.

4.1.2 Assumptions and parameters for the micro-CHP model

For the µCHP system model described above, there are several assumptions made.

- Hourly time step: Being reported by [a34], modeling the performance of µCHP system is highly dependent on the temporal precision. For instance, the simulated results with 30-minute demand precision data vary significantly from the 10-minute data precision, and little difference in the outcome is observed for demand data precision vary below 10-minute. However, to simulate the optimized operation of the XRGI15 based µCHP system, the time step is assumed to represent a time interval of 1 hour in this case. This assumption is made due to the available demand information for a Danish household which is measured on hourly basis and the present spot prices for electricity in Nordic countries are also hourly prices which are derived from the day-ahead wholesale market.

- Day-ahead generation schedule based on flawless predictions: Solutions to the modeled optimization problems are actually the generation schedules for the next period T e.g. next 24 hours, derived based on the forecasted information, including demand and prices for every hour. Therefore, when real-time comes the system is locally controlled to exactly follow the generation schedule. Of course, flawless predictions are implausible in practice. Thus, in real-time operation, which is not simulated here, the optimization can be run repeatedly at the beginning of each hour to optimize the generation for the rest of the day, taking into account the adjusted forecasting information and the corresponding system status.

- Start-up time, shut-down time, Minimum on/off time are not considered: For the ICE/Stirling-based µCHP systems, the µCHP unit can be generally started very fast within a few minutes. In order to prevent frequent on-off switches of the engine, the minimum on/off times of 30 minutes or an hour are normally required by the manufactures [a35],[a36][a37]. As the simulation is carried on hourly basis, these technical constraints are modeled. For the gas-fired boiler, it is also assumed the start-up and shut down occur instantaneously.

- System efficiencies: Linear generation characteristic for the µCHP unit is assumed, resulting fairly realistic system efficiencies for part-load and full-load conditions. As for the gas-fired boiler, constant thermal efficiency is assumed as long as the boiler is on.

- Heat storage modeling: The storage can be placed either in parallel or in series with the µCHP unit depending on the thermal load and the desired flexibility level. Small water tanks between 75 and 400 liters are normally placed in series with the µCHP system to meet the needs of space heating and domestic hot water for typical households. For the multi-family houses and buildings, the sizes for water tanks can go as large as 2000 liters and be placed in parallel with the µCHP unit [a56][r10]. In this case, as the XRGI 15 µCHP is simulated to meet the energy needs of a Danish multi-family house, the storage configuration is chosen as in parallel with the µCHP unit, shown in **Figure 4-4** as recommend by [a38]. In this storage tank, the hot water (top) and cold water (bottom) is divided through a separating layer. When heat is produced by the µCHP unit than the heat demand, the hot water is injected in top of the storage tank. This way of storing heat allows the storage to store almost a full tank of hot water which can be delivered when it is required. If the temperature for the cold water T_{cold} and the temperature for the hot water T_{hot} is provided, the maximum capacity of the storage can be calculated as $h_{smax} = mc\Delta T$, where m is the mass of water in the storage in kg, c is the specific heat capacity of water equals to 4.18J/(kg·K) and ΔT is the temperature difference. Furthermore, in the hourly based simulation, it is assumed that the lossless heat tank can be fully charged/discharged within one hour.

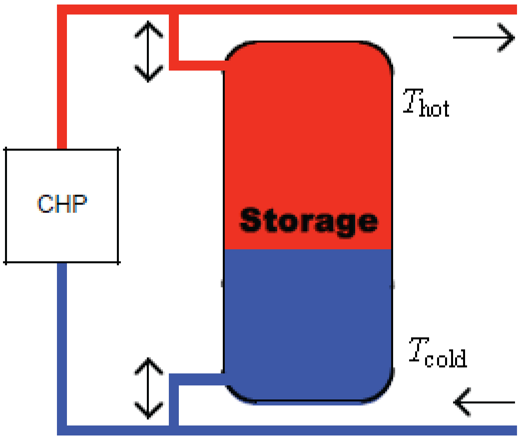

Figure 4-4: Heat storage configuration

- Heat dump is not allowed: Even though dumping the heat is possible and can provide more flexibility for electricity production. In this case, heat dump is banned due to the concern of energy wasting.

Based on the above assumptions, parameters for the XRGI15 based µCHP system are given in **Table 4-1**. $h_{smax} = 28kWh$

Table 4-1: Parameters of the simulated XRGI15 µCHP system

Parameter	**Comment**
$e_{chpmax} = 15.2kW$	Maximum and minimum electrical output of the µCHP unit
$e_{chpmin} = 6kW$	
$h_{chpmax} = 29.78kW$	Maximum and minimum thermal output of the µCHP unit
$h_{chpmin} = 16.9kW$	
$f_{chpmax} = 49.82kW$	Maximum and minimum fuel input of the µCHP unit
$f_{chpmin} = 25.9kW$	
$a_1 = 1.4, b_1 = 8.5$ $a_2 = 2.6, b_2 = 10.3$	Parameters in generation characteristic equations of µCHP unit (linear equations)
$h_{smax} = 28kWh$	Heat tank is in size of 475 liters with temperature range 20°C – 70 °C.
$h_{smin} = 0kWh$	
$f_{bmax} = 50kWh$	Maximum fuel input of the gas-fired boiler
$\eta_b = 80\%$	Boiler efficiency

4.2 Modeling the optimized operation of a direct controlled Virtual Power Plant

To explain the optimized operation of the direct controlled scheme, a µCHP systems constituted VPP, as shown in **Figure 4-5**, is modeled based on the model depicted in section 4.1. Each µCHP system is installed at the corresponding prosumer's household.

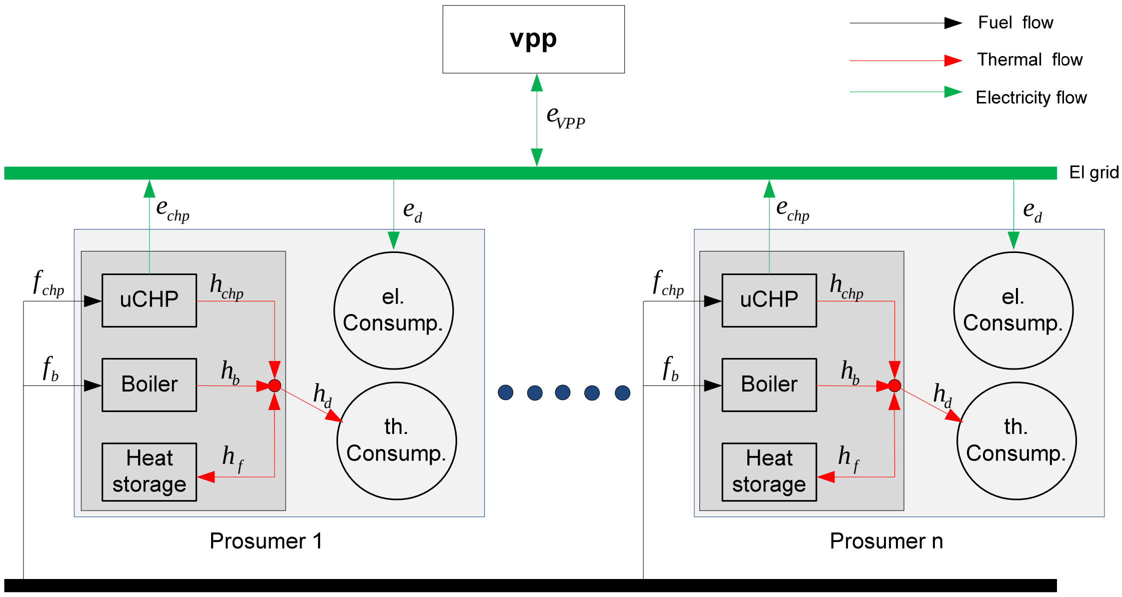

Figure 4-5: System structure for a *n* µCHP systems constituted VPP

After being aggregated by the direct controlled VPP, the prosumers will follow the dispatch orders delivered by VPP and the VPP functions as the energy supplier of the prosumer group. The objective of VPP thus turns into minimizing the overall system cost as well as assuring the energy supply of every prosumer.

Overall system cost can be expressed by (4.16), when the VPP is assumed to participate in the day-ahead market trading. Under this assumption, the electricity bought/sold from/to the wholesale spot market $e_{vpp}(t)$ will be priced at the corresponding hourly price $\pi_e(t)$. And in the real-time operation, this optimization process is repeated following the updated forecasting information, balancing requirement and the economic signals.

$$COST = \sum_{t=1}^{T} cost_{vpp}(t) = \sum_{i=1}^{N} f_{vpp}(t) \cdot \pi_f(t) + e_{vpp}(t) \cdot \pi_e(t) \qquad (4.16)$$

And the overall fuel consumption $f_{vpp}(t)$ and electricity exchange $e_{vpp}(t)$ with the grid for every single hour *t* are expressed in (4.17) and (4.18).

$$f_{vpp}(t) = \sum_{i=1}^{N} [f_{chp,i}(t) + f_{b,i}(t)] \qquad (4.17)$$

$$e_{vpp}(t) = \sum_{i=1}^{N} [e_{d,i}(t) - e_{chp,i}(t)] \qquad (4.18)$$

From (4.18), it can be found that the electricity generation within VPP is actually shared within the VPP framework before being traded in the market. In an ideal situation, it is even possible to assume there is a global heating network which further allows a shared heat production and heat storages within in the VPP framework; however, this turns out to be implausible for the present network since the heating network, unlike the electricity grid, is generally built for a limited area. Thus, besides changes made above, the optimization problem that has to be solved by the VPP still have to be subject to the local constraints from (4.1) to (4.10) for every prosumer. As for equation (4.15), this unit dependent constraint can be extended to system wide as given by (4.19). This extension excludes the heat cost incurred by initial stored heat when a short term optimization is performed.

$$\sum_{t=1}^{N} h_{s,i}(0) = \sum_{i=1}^{N} h_{s,i}(T) \qquad \textbf{(4.19)}$$

The above described operation strategy can be taken as one kind of model predictive control (MPC) [a41][a42] , the control actions exercised by VPP are based on all relevant information about the VPP system (models for the prosumer group) and the external factors (demand and electricity prices). The overall control schematic for the modeled direct controlled VPP is given in **Figure 4-6**. Disturbances in the real-time operation can be either caused by the internal variations (load variations and forecasting errors, etc.) or coming from externally (possible intraday transactions or requirements from other parties like TSO due to security concerns). In the following simulation, the predictions are assumed to be perfect and the control actions can be carried out flawlessly.

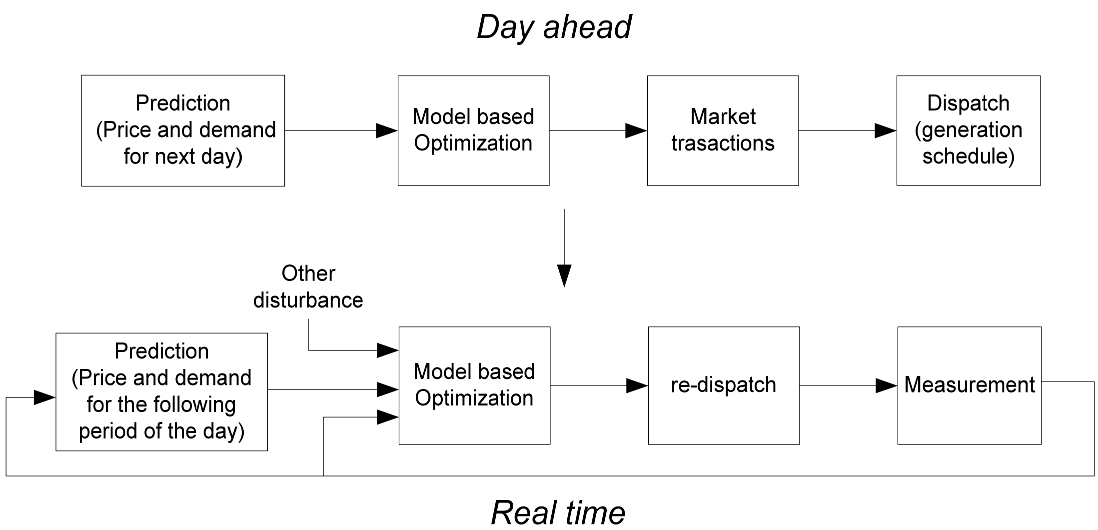

Figure 4-6: Schematic of MPC for direct controlled VPP

4.3 Simulating a 10µCHP constituted Virtual Power Plant

In this section, 10 identical XRGI15 µCHP systems, based on the models and parameters given in section 4.1 have been deployed in 10 Danish multi-family houses. These prosumers are further aggregated by a direct controlled VPP, which intends to trade electricity in the day-ahead electricity market while meeting energy demand of these prosumers. 10 winter day load profiles which are assumed to be forecasted day-ahead are generated[6] and applied to the 10 prosumers respectively as shown in **Figure 4-7**, and the forecasted electricity spot price for that winter day in 2006 is taken from [w12] and shown in **Figure 4-8**. The heat peak load takes place twice in the typical winter day at around 7am and 8pm respectively. While the electricity peak load occurs at night around 7pm, at which time the electricity price also reaches the peak value of that day.

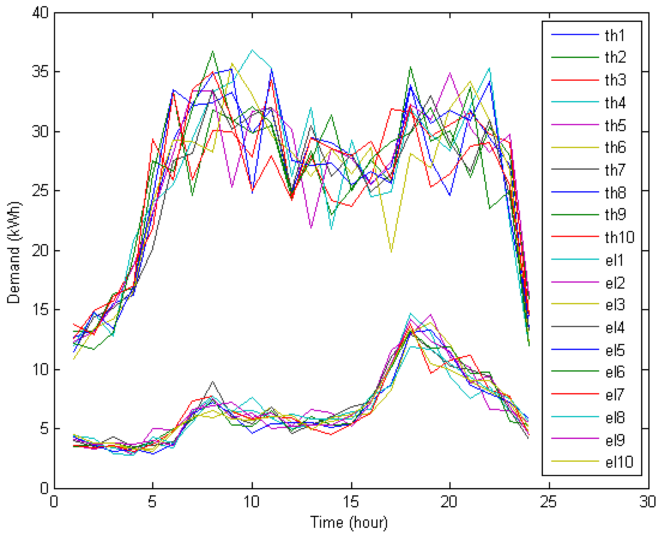

Figure 4-7: Winter load profiles of the10 multi-family houses

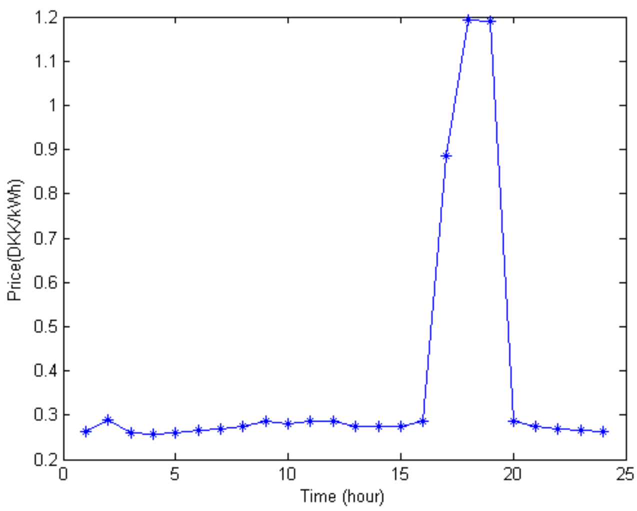

Figure 4-8: Electricity spot prices for the simulated winter day

[6] Details of generating the load profiles are given in Appendix A.

For this single day simulation, the total time steps T is given to be 24 and the number of µCHP systems n is assigned to be 10. The natural gas price is assumed to be 0.36dkk/kWh (excl. tax) for all simulated hours [a39]. And the **G**eneral **A**lgebraic **M**odeling **S**ystem (GAMS) is used to model and solve the corresponding problem.

4.3.1 Generation schedule derived from day-ahead

Provided the demand and price information known day-ahead, the VPP can solve the MIP problem and deliver the generation schedule for every prosumer $e_{chp,i}(t)$, as given in **Table 4-2**.

Table 4-2: Hourly generation schedule for individual µCHP system
(Total system cost=3056DKK, solving this problem takes 998.28sec with GAMS)

power(kW) / hour	chp1	chp2	chp3	chp4	chp5	chp6	chp7	chp8	chp9	chp10
2	8.00714	8.91429	9.31429	6.95	6	6.15	8.48571	7.92143	6	6
5	0	0	0	0	0	0	0	0	0	6
6	6	6	0	6	6	0	6	6	6	0
7	0	0	6	0	6	6	0	6	6.35	6
8	6	6	6	6	6	6	6	6	0	6
9	6	6	6	6	6	6	6.01857	6	6	6
10	6	6	6	6		6	0	6	6	0
11	6	6	6	6	6	6	6.41	6	6.25	6
12	6	6	6	6	6	6	6	6.11429	6	6
13	6	0	0	6	6	6	6	0	6	6
14	0	0	6	6	0	0	0	6	6	0
15	6	6	0	0	0	0	6	0	0	6
16	0	0	0	6	6	6	0	0	0	0
17	6	6	6		6		6	6	6	6
18	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2
19	6	6	6	6	6	6	10.11429	6.04286	11.19286	6
20	0	0	6	6	6	6	0	6	0	0
21	8.87143	6	6	6	0	6	7.60714	6	7.32143	0
22	0	6	0	0	6	0	0	0		6.52143

Based on the individual generation schedules, the aggregated generation schedule of can be derived, as shown in **Figure 4-9**. The red bars indicate the amount of electricity that the VPP is willing to produce and sell at the corresponding hourly spot price, while the blue bars represent the amount of electricity it has to buy from the electricity day-ahead market. The resulted difference between the amount of electricity to buy and to sell will be transformed into the bids/offers submitted to the day-ahead market. Once the transaction is completed, the individual generation schedules will be delivered to each prosumer and implemented in the next day.

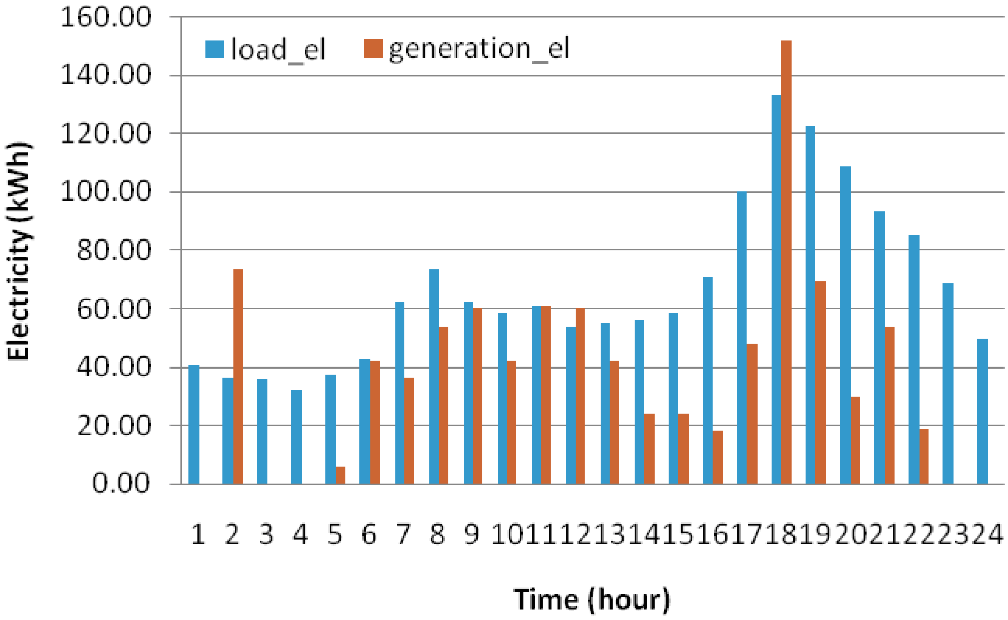

Figure 4-9: Aggregated transaction schedule of the VPP

4.3.2 Redispatch in the real hour

In the real hour operation, there are internal unbalances due to forecasting errors and also possibilities for the VPP to trade electricity again in the intra-day market (exchange) or through the over-the-counter contract (bilateral contract) to increase the revenue or to hedge the risk. Therefore, the decision makings faced VPP operator is a continuous process and redispatch is carried out to minimize the incurred balancing cost.

In these cases, the predicted information included in the MPC covers the estimated unbalance and the regulating prices. Generally, it can be assumed that for a given hour the internal unbalance due to forecasting errors before redispatch for that hour is estimated as $\Delta P(t)$. And the energy balance for that hour during redispatch has to be reformulated as given in (4.20). (To get rid of the symbol conflictions, a prime symbol is added to every variable described above.) It means that the VPP can reduce the unbalance internally by redispatching the µCHP systems, resulting in the modified energy exchange with the grid $e'_{vpp}(t)$.

$$\sum_{i=1}^{N} e'_{chp,i}(t) + e'_{vpp}(t) = \sum_{i=1}^{N} e_{d,i}(t) + \Delta P\ (t) \qquad (4.20)$$

The real unbalance after redispatch that will be penalized by TSO is thus the difference between the day-ahead committed amount of energy exchange and energy exchanged in real-time $\Delta P'(t)$ can be found as in (4.21).

$$\Delta P'(t) = e_{vpp}(t) - e'_{vpp}(t) = \sum_{i=1}^{N} e'_{chp,i}(t) - \sum_{i=1}^{N} e_{chp,i}(t) - \Delta P(t) \tag{4.21}$$

The hourly cost which after redispatch is expressed in (4.22).

$$cost'_{vpp}(t) = \sum_{i=1}^{N} f'_{vpp}(t) \cdot \pi_f(t) + e_{vpp}(t) \cdot \pi_e(t) + \Delta P'(t) \cdot \pi_{reg}(t) \tag{4.22}$$

where

$$\pi_{reg}(t) = \begin{cases} \pi_{e,up}(t) & if\ \Delta P'(t) \geq 0 \\ \pi_{e,down}(t) & if \Delta P'(t) < 0 \end{cases} \tag{4.23}$$

The reformulated cost function includes the fuel cost after the system being redispatched, the cost for already committed energy exchange and the balancing cost charged by TSO. In (4.23) the balancing price is expressed, implying both underproduction situations and overproduction situations will be punished by the TSO[7]. Therefore, by minimizing the overall cost as given in (4.24), the system can be optimally redispached taking into account the forecasted unbalances for every hour and the associated balancing cost. During this optimization, constraints (4.1) to (4.13) and (4.17) to (4.19) still have to be satisfied, however all variables inside are replaced by the same expressions with primes respectively, indicating the redispatched system information.

$$COST' = \sum_{t=1}^{T} cost'_{vpp}(t) \tag{4.24}$$

In this section, a special case is simulated. It is assumed that 50kWh extra generation is required for the 1st hour of the operation day by the TSO as a balancing requirement since the VPP has unused generation capacity and the VPP does not have any internal unbalances. Apparently, to fulfill this order, the VPP has to redispatch the µCHP systems and this operation may result in deviations from the scheduled generation for the following hours. If the VPP cannot mitigate the resulted unbalance before the delivery, these deviations will be penalized at balancing prices posted by the TSO. Thus, the VPP has to redispatch the µCHP systems in order to minimize the extra cost associated with the 50kWh generation.

[7] This is not always true. In practice, the supply and demand mismatch has to be mitigated by the TSO through the regulating market. If a genco can not produce as much as contracted, the genco has to buy balancing power from the TSO at the up regulation price, which is normally higher than the spot market price. If it produces more than contracted, the genco has to sell the balancing the excessive production to the TSO at the down regulation price, which is normally lower than the spot price.

To emulate the decision making for redispatch, the problem is reformulated based on the pre-described redispatch model. By assuming no internal imbalances caused by forecasting errors, the reformulated energy balance for hour 1 is expressed by (4.25), and $\Delta P(t)$ is therefore zero.

$$\Delta P'(1) = \sum_{i=1}^{10} e'_{chp,i}(1) - \sum_{i=1}^{10} e_{chp,i}(1) = 50 \tag{4.25}$$

The corresponding overall cost objective function is given in (4.26). The 50kWh incurred regulating cost is subtracted from the system cost since the extra generation is called by TSO as balancing services.

$$COST' = \sum_{t=1}^{T} [\sum_{i=1}^{N} f'_{vpp}(t) \cdot \pi_f(t) + e_{vpp}(t) \cdot \pi_e(t) + \Delta P'(t) \cdot \pi_{reg}(t)] - 50 \cdot \pi_{e,up}(1) \tag{4.26}$$

If up and down regulating prices for all 24 hours are assumed to be to as high as 11.2DKK/kWh and -11.2DKK/kWh (1.5euro/kWh) respectively[8], by solving the reformulated MIP problem, the rescheduled generation for individual µCHP system is found as in **Table 4-3**, and the resulted minimum system cost is founded as 3129DKK. Compared to original scheduled system cost 3056DKK, the additional cost caused by delivering the 50kWh to the third party is 73DKK. And the TSO should pay VPP at least 1.46DKK/kWh as the cost for calling this balancing service. Therefore, by providing this balancing service, VPP can make 50*(11.2-1.46) = 487DKK. On the contrary, if this 50kWh is the internal unbalance of VPP that caused bad forecasting, by making this kind of optimal redispatch, VPP can save 487DKK from the reduced payment on the unbalance cost. In **Table 4-4**, the resulted deviations from the original schedule are given, showing the generation schedule collected after redispatch is very close to the original schedule in the case of high regulating prices.

[8] In practice, the balancing prices are not like the provided extremely high values, unless large system unbalances are encountered. Here, the high balancing prices are assumed to indicate the fact that the real-time deviations from the scheduled generation are heavily penalized by the TSO. In such case, the VPP operator should try to keep the redispatched generation schedule as close as the original generation schedule.

Table 4-3: Rescheduled generation for individual µCHP system

power(kW) / hour	chp1	chp2	chp3	chp4	chp5	chp6	chp7	chp8	chp9	chp10
1	6	6	6	6	0	6	8	0	6	6
2	6	6	6	6	9.3	6	12.62857	9.81429	6	6
5	0	0	0	6	0	0	0	0	0	0
6	6	6	6.55	0	6	0	0	6.11429	6.35	6
7	6	0	0	6	0	6	6	6	0	6.35
8	0	6	6	6	6	6	6	6	6	6
9	6	6	6	6	6	6	6	6	6	6.66142
10	6	6	0	6	6	6	6	0	6	0
11	6	6	6	6	6	6	6	6	6.13571	6.52429
12	6	6	6	6	6	6	6	6	6.11429	6
13	6	6	6	6	6	0	0	6	6	0
14	0	0	0	0	6	6	0	6	6	0
15	6	0	0	0	0	0	6.50714	0	0	11.49286
16	0	0	6	6	0	6	0	0	0	0
17	6	6	6	0	6	0	6	6	6	6
18	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2	15.2
19	6	6	6	6	6	6	10.11429	6.04287	11.19286	6
20	0	6	6	6	6	6	0	0	0	0
21	0	8.21429	6	6.65714	6	6	7.60714	6	7.32143	0
22	8.87143	0	0	0	0	0	0	6	0	6.52143
21	0	8.21429	6	6.65714	6	6	7.60714	6	7.32143	0
22	8.87143	0	0	0	0	0	0	6	0	6.52143

Table 4-4: Deviations from the original generation schedule

power(kW) / hour	VPP Unbalance
1	50
6	1.01429
9	0.64285
22	2.87143

The above elaborated redispatch program, as a result, decides and regulates the operation for the 1st hour and delivers the updated schedule for the following hours of the corresponding day. In case the VPP encounters real-time unbalances or is called to provide balancing services, this program can be recalled repeatedly to make optimal real-time redispatch.

4.4 Summary and discussions

This chapter looked into the optimized operation of the direct controlled VPP with µCHP systems. Through the aggregation, the prosumers with µCHP installations can benefit from the volatility of wholesale electricity prices. The economic benefits brought to individual prosumers are not analyzed in the chapter, but can be found in [a24] (also attached to Appendix D) which reports that when the electricity tariff for the µCHP system is changed from the fixed tariff to the hourly market spot prices a single prosumer can make around extra 20 euro earnings per year. Even though the earning is very little, around 1000 kWh extra electricity can be generated at mostly high spot price periods in a year which can significantly help to meet the electricity scarce of peak load periods. Further, as simulated in section 4.3, the aggregation allows the prosumers to provide balancing services to the parties in need, which can also bring in extra earnings to the prosumers and contribute to the overall system operation.

The µCHP system modeled in this chapter is a very specific system with linear generation characteristics and some stringent constraints. Relaxing the constraints such as prohibition of heat dump can affect the decisions made by the VPP and the associated economic performance. However, usage of the least cost control algorithm simulated in this chapter is not limited to the presented µCHP and VPP system.

For the presented direct controlled VPP with an extremely centralized control structure, the VPP operator schedules the DER plants and issues dispatch instructions to modulate output in the light of changing conditions. The operator may also arrange ancillary services, such as frequency response and voltage control and sell these services through the related market. In [a40], the direct-controlled operation scheme for the VPP is demonstrated to show the possibility of providing reactive power supply with the objective to minimize network congestions and operational costs. In case the VPP wants to achieve multiple value streams such as providing different services simultaneously, these problems can be formulated as multi-objective optimization problems to support the decision makings.

In principle, operating the direct-controlled VPP has no difference compared to operating a conventional power plant as long as the communication is flawless. However the computation load and information load incurred during the decision making process will be quite heavy for when a huge number of small units are grouped. If the deterministic models are replaced by stochastic models, these problems will be much more intractable. Apparently, it would be almost impossible for the VPP to make optimal real-time decisions if thousands of prosumers are waiting for orders. As a result, if a VPP wants to aggregate a large number of DER devices, decentralized control structure becomes a necessity.

5 PRICE SIGNAL CONTROLLED VIRTUAL POWER PLANT

As a special group of technologies dedicated to the high efficient electrical generation/consumption at the customer side, the prospect of independent ownership for DER is inevitable. In response to the growing number of these units, the VPP-like aggregators require new means for coordinating the DER operations rather than simply choosing the centralized control schemes. This need is mainly due to the following concerns associated with the centralized control schemes: a) the enormous investment in upgrading the current communication system to a fast and reliable two-way communication system; b) the ever-increasing computation requirement for optimally deciding the setting points for thousands or more DER devices; c) the unfavorable opinions on letting other parties control the devices installed at private residential premises; d) the vendor lock-in issues may arise since an individual VPP has to install its own smart boxes embedded with its own VPP- logic at all the customer side to exactly execute the VPP orders.

This chapter looks into one mechanism available for the VPP to coordinate a great number of small-scale individual units on different time scales, known as “price signal control” or “price-based control”. Under this scheme, the relationship between VPP and DER can be simply described as “rate and react”. The VPP conveys the appropriate real-time price signals to the DER to regulate the electricity generation/consumption (one-way communication), while the DER can decide to react or not based on their local context. The HEMS, which centrally aggregates and controls the DER and other passive loads at home-level, can integrate the control systems of different DER and other necessary functions e.g. logging, reporting, etc., and function as the local price-responsive controllers.

The theory and development of “price signal control” is briefly reviewed in Section 5.1. In Section 5.2 the price signal controlled VPP scheme is proposed and explained. This idea is further demonstrated in Section5.3 by modeling and simulating a VPP with 100 prosumers. The DER devices based on different µCHP technologies such as ICE-based µCHP systems and PEMFC µCHP systems, etc. are installed at the individual premises of each prosumer. The simulated VPP uses **A**rtificial **N**eural **N**etwork (ANN) based identification model to estimate the price responsiveness of the prosumer group. The chapter ends with discussions and conclusions in Section 5.4.

5.1 Theory and development of price signal control

In early 1980s, “spot pricing” also known as responsive pricing or real-time pricing, was developed by Fred C. Schweppe and his coworkers. Their ideas were detailed presented in [b5] with mathematical derivation and descriptive discussions. The spot price depicted in [b5] , in general terms, is developed based on energy marketplace and reflects the operation and capital costs of generating, transmitting and distributing electricity for a specific moment. From then on, the topic of price signal operation of electrical power systems becomes attractive to every party involved in the electric power system society: the utilities, the system operators, the market operators, the researchers and the engineers, etc.

The basic theory of price signal control can be found in **Figure 5-1**, which illustrates how a current liberalized electricity market is cleared. The market clearing price or equilibrium price π^* is found when the quantity that suppliers are willing to provide is equal to the quantity that consumers are willing to obtain. In this market, both supply curve and demand curve are derived from the independent actions of suppliers and customers as they respond to price changes according to their own price elasticity[9]. If the market clearing price is deliberately changed, such balance between supply and demand is obviously broken; however, it straightforward shows the feasibility of price signal control.

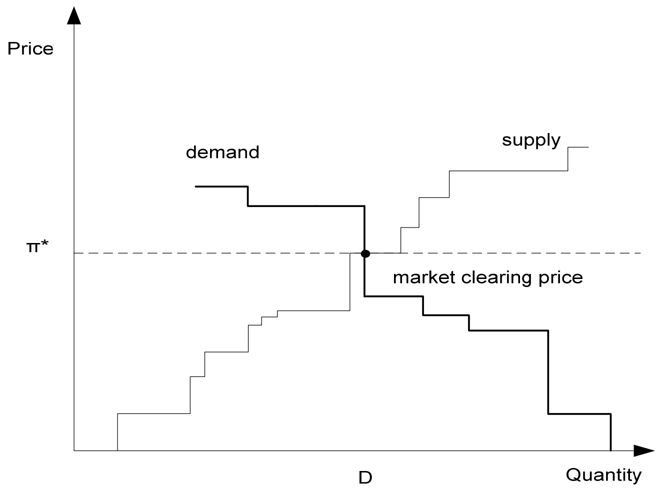

Figure 5-1: Market clearing in a liberalized electricity market

[9] Price elasticity is defined as the percent change in quantity (demand or supply) for a given percent change in price.

5.1.1 Controlling the generation

In a electricity market, the supply side is constituted by a number of generators based on diversified generation technologies. Since the production of a single generator i is very small compared to the size of the market, the market price hardly can be affected by the its generation P_i , expressing the fact that this generator is a price-taker.As all generators can be characterized most basically as a device capable of delivering at any given time electricity at a price which makes its running profitable, their decision making process can be formulated by solving an optimization problem. The objective is given by (5.1) as maximizing the difference between the revenue resulting from the sale of the electricity it produces and the cost of producing this amount of energy, subject to constraints like (5.2) which guarantees the profitable generation and (5.3) which depends on the technical characteristic of a generator[10].

$$\max \quad Profit(i) = \max\,[\pi \cdot P_i - C_i(P_i)] \tag{5.1}$$

where P_i is the power produced by generator i during a certain period, π is the price at which the electricity is sold and $C_i(P_i)$ is the cost of producing the electricity.

$$\pi \cdot P_i - C_i(P_i) > 0 \tag{5.2}$$
$$P_{min,i} \leq P_i \leq P_{max,i} \tag{5.3}$$

Apparently, changing the electricity price to a great extent affects the decision made by a generating company. Even though the price responsiveness of a generator, which implies how a generator responds to different market prices, is tightly related to the generator characteristics e.g. cost functions (quadratic or piecewise linear, etc.) and technical constraints, and often unknown to the system operators, there exits the feasibility of controlling the generation with price signal.

Such feasibility has been thoroughly investigated by Alvarado and his co-workers. In [a43][a43][a45][a46][a47], from the perspective of an independent system operator (ISO), they have addressed a set of issues arisen when using price signal control when the cost information of individual generators are unknown, including the requirement on cost functions (quadratic or piecewise linear), the response dynamics, non-stationary costs and market power issues.

1) Regarding the cost function issues, the authors concluded that a system with its generators' cost functions expressed in quadratic manners can be optimally controlled by the ISO who could post correct price signals based on his knowledge

[10] For simplicity purposes, a lot of physical constraints associated with the characteristic of a power plant, e.g. minimum on/off time, reservoir limits for associated storage facilities, etc. are not listed.

over the cost functions. Such knowledge can be obtained by carrying out enough observations about the behaviors of the generators to price signals when their cost functions are unknown. About the linear cost functions, although their all-on all-off characteristics seem erratic under extreme conditions, the involvement of line losses in finding the optimal price signals could improve the result since the line losses can be expressed by quadratic functions of the power injection at either node of a power line.

2) Response dynamics of price signal control refers to the delays incurred within this system. These delays can be caused by either the price makers in determining and posting of prices or the generators who have ramping rate limitations. Although these delays can not be eliminated, when appropriate time cycle for the price adjustment is selected, it would be possible to attain a “near optimal” cycle response by alternating sequence of prices.

3) When the costs of generation vary over time, the difficulty of an ISO to predict the generators’ response to a posted price is greatly increased. One way to address this issue is to investigate a more complete model of the generator cost structure and try to identify the corresponding parameters through a series of observations. Another way for ISO to solve this issue is to use feedback observations and find out the generators which have the non-stationary costs and reevaluate the price response based on updated information.

4) In the case of control by price, the only way for a generator to exercise its market power is to withhold its generation capacity and wait for a higher price. To detect the market power, the consistency between the predicted behavior and actual behaviors for price-taking generators can be checked. Therefore, the market monitoring schemes should also be integrated into the price signal control system.

In practice, controlling the generation by price signals may be often seen as using Locational Marginal Prices (LMPs), also called nodal prices, to manage the efficient use of the transmission system when congestion occurs on the bulk power grid. Such market pricing method is widely used in PJM, New York systems, New England markets in the USA and in New Zealand. Generators are paid location-specific prices which are derived from a bid-based, security-constrained, economic dispatch. In [w13], a detailed description about how to calculate the LMP can be found. However, as the generators have to bid in the market rather than waiting for a posted price, the issues mentioned with price signal control are not fully reflected by the LMP-based market operations.

Another example of using price to control the generation can be found in [a48], wherein a special price signal controller is developed for the generators in India to meet the requirement of improving the behavior of system frequency. In India, the unscheduled interchange (UI) of a generator is priced according to the frequency change, as shown in **Figure 5-2**. In case the real-time generation deviates from its scheduled output, the UI rate will be used to price the deviation in every 15 minutes. Under this circumstance, an automatic price signal controller was introduced to replace the manual control. Also, there is a lack of practical information to evaluate this frequency related price signal control scheme.

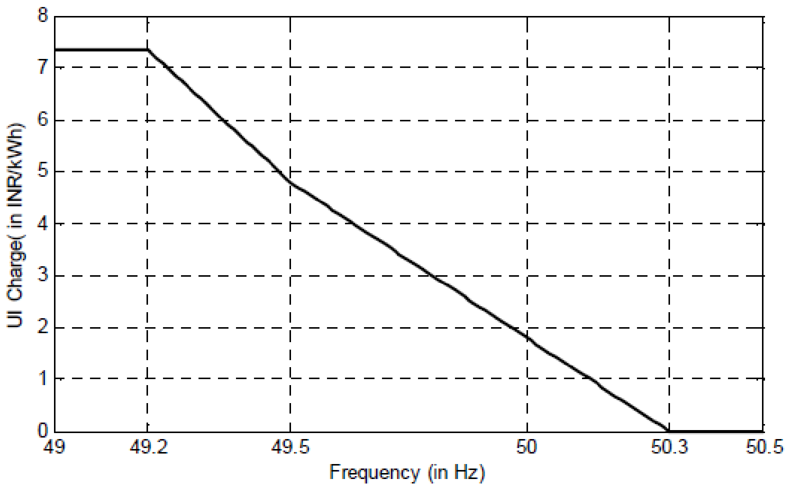

Figure 5-2: UI price vs system frequency

5.1.2 Controlling the demand side

In reality, the demand curve, which was shown in **Figure 5-1**, looks more like a hockey stick as illustrated by D1 in **Figure 5-3**. The crossing point between supply curve S and the inelastic demand curve D1 indicates a relatively high electricity price π_1. If the demand side can achieve more elasticity, as illustrated by D2, a certain demand reduction will result in a significant price drop, which implies a huge amount of saving on the generation cost.

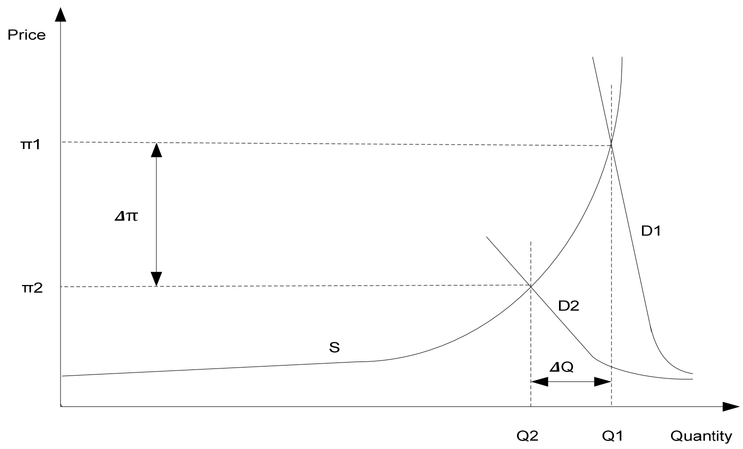

Figure 5-3: Principle of demand response

To manage the customer consumption of electricity in response to supply conditions and achieve more demand side elasticity, time-based pricing, which is used to price the electricity sold in the retail market, have been widely used by the utilities for many years [a56][r11]. Although in some sense time-based pricing is often seen as an incentive which results in voluntary customer responses, from the utility's perspective, it also can be regarded as an open loop control wherein the utility has to predict the price response. Normally, time-based pricing includes both static time-varying retail prices generally called **T**ime-**o**f-**U**se (TOU) prices and dynamic prices.

TOU prices are always preset for specific time periods of a day; usually including peak, shoulder and off-peak three time blocks. The rates for each time block are adjusted normally a few times per year, leading to the fact that the price is the same at a given period of day throughout a whole season. Despite such pricing scheme neither captures the hour-by-hour variation in the wholesale cost of electricity nor contributes to the real-time power system operation, many electricity consumers especially large industrial and commercial customers have adjusted their electricity usage in accordance to the TOU prices which helps to shifting the load out of the peak load hours and increase the price elasticity on demand side [a49].

Compared to the static prices, dynamic prices are allowed to change more frequently, often a day of less. Being the most often used two types of dynamic pricing schemes, **C**ritical **P**eak **P**ricing (CPP) and **Real-time P**ricing (RTP) are developed to capture the electricity market changes and encourage the demand elasticity.

CPP allows for the retailer to occasionally declare high retail price for critical peak hours for a limited number of times in a year. When this program is called on, the customers will be notified in advance that the relatively high peak prices are approaching. Since CPP value is not necessarily the market value of the power, it can be any value that is necessary to obtain the desired amount of load reduction. Therefore, to determine the CPP tariff, a thorough study on the demand elasticity has to be carried out. As denoted in [a49][a50], CPP is more effective than TOU in increasing the demand side elasticity and can result in a moderate level of reduction of annual electricity bills for different group of customers.

RTP introduces economic incentives by allowing the retail price to change hourly or at even shorter time intervals. The real-time price for each hour can be announced in advance from a few minutes to a day. Obviously, a shorter lag time between the price announcement and the price implementation will result in prices that more accurately reflect the actual situation of the electricity market and power system operation. In practice, the RTP can be applied either alone (one-part tariff) or together with a standard energy price (two-part tariff). In a one-part RTP tariff, it typically reflects the marginal generation cost of that moment. While two-part RTP tariff is commonly used by the utilities wherein a customer baseline load shape is formed based upon his historical load prior to going on RTP. The baseline load, regardless of the real consumption will be charged at a standard energy charge and the hourly load deviations from the baseline are priced at RTP. In both cases, the RTP has to be calculated and posted before all settlement computations have been finalized in order to stimulate the customers' interest in responding to the varying price signals. From the perspective of the retailers, this requires them to have more accurate load forecast based on the statistical study of historical price responsiveness of their customers in order to minimize the forecast error. Although the real RTP should the real-time marginal generation cost for meeting the real-time demand, a portion of the estimated benefits or costs used for risk hedging might be added by the retailers, resulting higher values of RTP. In terms of the advantages introduced by RTP, a lot of experience accumulated in pilot projects described in [a56][r12][r14] and [a51] shows that RTP could have significant impacts on increasing the demand side elasticity and reducing the electricity bills for the customers.

5.1.3 Price responsiveness of Distributed Energy Resources

Basically, DER is no different than the conventional generation technologies or demand response programs, and can also be controlled by price signals. Despite the control algorithms implemented by the DER manufacturers, the short-term price responsiveness of different DER technologies is closely dependent on their short-term economics and can be classified into three categories: cost-based response, users' willingness based response and the response of the DER which rely on the intermittent renewable energy resources.

Cost-based response: In this group, DER technologies running on fossil fuels like the diesel/gas generators have specific amounts of operation costs to be recovered. Thus their price responsiveness depends on the fuel price and the parameters e.g. start-up/shut-down costs, generator fuel rate and least-on/off time, etc. of the DER which contribute to their cost functions. The electricity price history does not play a role here.

Users' willingness based response: Compared to the DER technologies listed in the former group, the price responsive loads e.g. the heat pumps, etc. and the storage technologies e.g. batteries for EVs, etc. are more dependent on the users' willingness on shifting their consumption from a relatively high price period to a low price period. Thus the price responsiveness of the DER within this group is highly related to the electricity price since the users will use it to weigh the money gains and the comfort losses.

Renewable DER with intermittent characteristic: Renewable DER with intermittent generation characteristics like wind turbines and PVs, where the output is controlled by the ambient conditions, may response to any positive price signals and generate as much as they can due to their little variable costs.

It has to be noted that the price responsiveness of some DER technologies can be found based on a mix of the cost-based response and willingness based response. The µCHP is a good example of these DER technologies. Because the µCHP is primarily used to meet the thermal demand of the local premises, the coupled electricity production is normally considered as by-product. In such case, to regulate the electricity production of a µCHP implies the change of its thermal production which in turn affects the user comfort. However the electricity generation could also depend on the cost of operation if the users' comfort can be guaranteed by the involvement of a heat storage buffer. Several examples about the price-responsiveness of the µCHP system can be found in [a52] (also given in Appendix D). For the µCHP systems, when linear models are used to represent the generation characteristics, they always produce at the maximum or the minimum generation level when the electricity price is above the system marginal cost and there is enough storage capacity available in the water tanks. This implies the fact that using price signals to control the µCHP systems are much more like an all on or all off control when the aggregated µCHP systems are identical. To tackle this problem, the price signal controlled VPP must have a mixed generation portfolio.

5.2 Developing price signal controlled Virtual Power Plant

In a VPP, the DER are aggregated in order to break the electricity market capacity barrier for profitable transactions or to provide specific services such as load following, load peak shaving, energy balancing and power balancing, etc. to the other entities. As the DER are typically in range of several to tens of kW, to reach a generation capacity level comparable to a conventional power plant requires hundreds to thousands of these small-scale units to be aggregated by the VPP. For the conventional direct centralized control scheme, computation load and communication load is inevitably high for the

VPP operation system. Alternatively, the “price signal control” concept is more suited to control a large number of small-scale units as the computation load is distributed to every single DER unit and the information need to be communicated between VPP and DER in real-time (e.g. every 15 minutes) is only the price signal and the metered data if necessary. It is also possible that the metered data for individual DER is stored in a local database and delivered to VPP with a much lower frequency (e.g. once per day) to perform subsequent settlement.

In **Figure 5-4**, one possible structure of the price signal controlled VPP is presented. The VPP server mainly comprises three functional modules: Prediction, Identification and Optimization.

Prediction: The response of DER to price signals as discussed in section 5.1.3 depends on not only the technical characteristic DER but also the local context such as electrical and thermal demand, wind speed , etc. In order to predict the DER price response, these information is necessary. Besides, VPP may also have to forecast the market price in order to develop appropriate price signals which benefit both the VPP and the DER owners.

Identification: As the knowledge of price responsiveness of the DER participants being accumulated, a black box model representing the DER group can be found. With this black box model, the VPP operator could estimate the dynamic price response of the DER participants. It is not necessary to have only one identification model if the combination of several models representing the DER response at different periods e.g. seasons can result in a better performance.

Optimization: Since the VPP operator is not only a controller of the DER but also a market player in the wholesale market, the VPP may have multiple objectives to be fulfilled. In one case, one may imagine that when the VPP has already forecasted the hourly market prices for the next day, it has to post a number of price signals to the DER participants. Instead of posting the true market prices, VPP can alternatively post a set of lower prices which may result in almost the same DER response to increase its profit margin. In another case when the VPP could sell power at different markets, such as spot market and ancillary service market, it also needs the optimization module to help with optimal allocation of the available DER resources.

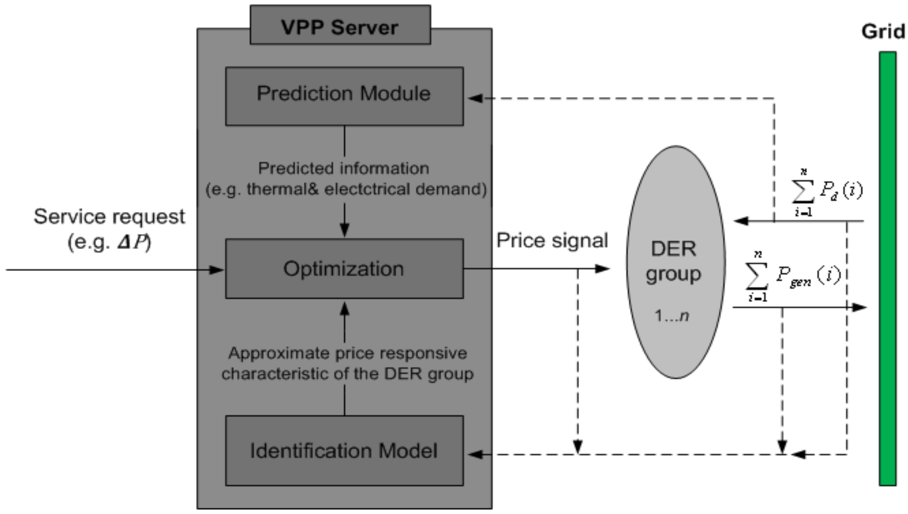

Figure 5-4: Structure of a price signal controlled VPP

Once a service request is sent to the VPP, the Optimization module, which follows the pre-designed optimization algorithm, will decide and deliver a single or a series of price signals based upon the predicated information (e.g. the local demand for the DER group in the upcoming price controlled period) provided by the Prediction module and the approximate price responsive characteristics of the DER group provided by the Identification model. The price signals will be further delivered to the DER group to acquire the requested generation. The individual DER unit i, following the posted price signal and its local context, will thus deliver the corresponding generation $P_{gen}(i)$, resulting in the overall generation $\sum_{i=1}^{n} P_{gen}(i)$ of the VPP, which aggregates n DER devices.

To continuously improve the quality of the Identification model, the information of the price signals and the overall generation of the DER group as well as other necessary information such as local demand, etc. must be recorded offline, as indicated by the dashed arrow lines in **Figure 5-4**. Likewise, the prediction model should be calibrated, in order to guarantee its accuracy on reflecting the future context.

Apparently, this sort of closed loop control considerably reduces the potential communication overhead in two-way communications compared to the direct controlled VPP presented in Chapter 4. Further, as the VPP use the aggregated information to develop an identification model, it is less relevant for the VPP to know what kind of DER technology is being aggregated which further reduces the information volume that has to be handled during decision making processes. In other words, the VPP regulates the overall electricity generation or demand of a prosumer without knowing what DER devices that prosumer have installed. With respect to providing services with very different time requirements, the VPP can post price signals at different time scales (e.g. hourly price, 15-minute price) to keep the consistency. The DER owners are thus granted with more freedom in choosing the appropriate price schemes that best fit their DER characteristics and their confort level preferences. Further, the transparency level is also relatively high for the DER owners, who can retrieve both the current price and the historical prices.

5.3 Simulating a price signal controlled Virtual Power Plant

In this section, a price signal controlled VPP with 100 prosumers is simulated. Each prosumer here is assumed to have a µCHP system installed at his household. The prosumer aims to optimize the µCHP operation in accordance with his local load demand and the external factors such as electricity price and fuel price, etc. broadcasted by the VPP. The intention of the VPP is to estimate the price responsiveness of the prosumer group under different conditions and to regulate the production of the prosumer group to follow pre-defined demand profiles by posting appropriate price signals. ANN is chosen to identify the dynamic response to varying price signals of this prosumer group.

5.3.1 Modeling and simulating the prosumers' price responsiveness

In order to emulate the price signal controlled VPP presented before, a group of 100 prosumers is modeled in this section. In the premises of every prosumer, a µCHP system is installed to meet the individual consumption needs of that household. Least cost control based µCHP systems, as being modeled in Section5.2, are also applied in this section. For each prosumer, the optimization period in this study is selected as one hour rather than a whole day. In other words, the prosumer receives the price information for the next hour in advance (e.g. a few minutes) and determines the set points of their units for that hour only. To diversify the generation portfolios, four different µCHP units have been modeled: ICE-based XRGI13 (6-15.2kWe), ICE-based XRGI15 (4-13kWe), ICE-based DACHS µCHP unit from Senertec (5.5kWe) and PEMFC µCHP unit (0-9kWe). Further, the boiler efficiency and heat storage size for each µCHP system are randomized within predefined ranges to emulate the fact that the effectiveness of price signal control is directly correlated to how different the prosumers respond to price signals. Details about the generation portfolios can be found in Appendix B.

Demand profiles

100 demand profiles for the corresponding multi-families are generated on hourly basis as described in Appendix A. In the simulation, only the period of January 2006 which comprises 744 hours is used.

Historical price signals

To characterize the dynamic price response of the prosumers to different electricity price signals, the VPP needs a data base with historical information. To create such a data base, a virtual historical electricity price profile with 7440 random samples is generated, the histogram of which is given in **Figure 5-5** with the bin width of 0.2DKK.

The price for natural gas is assumed to be constant at 0.6DKK/kWh during the simulation period.

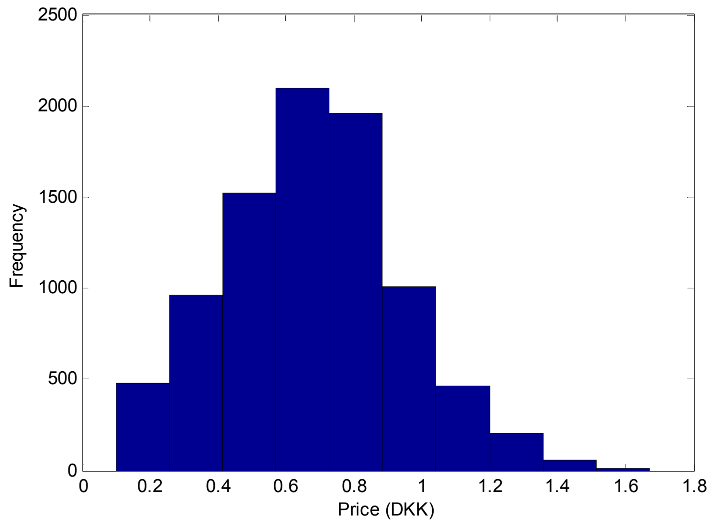

Figure 5-5: Histogram of the generated electricity prices

The generated electricity prices are taken as the hourly electricity prices posted by VPP in 10 consecutive Januaries as given in **Figure 5-6**. Such a price profile with very high volatility can be imagined as real hourly prices for a system with very high wind power penetration. The reason for not using the real spot market prices is due to the fact that to recognize the overall price responsiveness of the prosumer group, the price scenarios should not have a recognizable pattern like the real market prices which can only reflect how the DER respond to that price pattern.

Accordingly, the demand profile of January 2006, which includes 744 hourly demand values, is also repeated 10 times to establish a larger data sample. In order to better capture the price-responsiveness for the prosumer group under a certain circumstances such as a typical winter day, adequate price scenarios have to be simulated. For instance, if one price scenario results in one corresponding prosumer response based on one given demand profile for that hour, to fully capture a price change from 0.5DKK/kWh to 1DKK/kWh with a step change of 0.02DKK/kWh, 50 price scenarios are needed for that hour. As the prosumer group also has storage devices installed in their premises, the number of price scenarios in need becomes much larger since the simulated prosumer's response to the price signals not only depends on the current demand and prices, etc., but also relies on his former actions. For a day with 24 consecutive hours, if each hour has 50 price scenarios, provided a given load profile for that day, there will be 50^{24} price paths that may lead to different generation values. Apparently, when the prosumer group is taken as a black box, adequate historical data is important to the identification quality. Thus, for illustrative purpose, it is assumed that the aggregated prosumer responses in January to price signals are accumulated from 10 identical winter months.

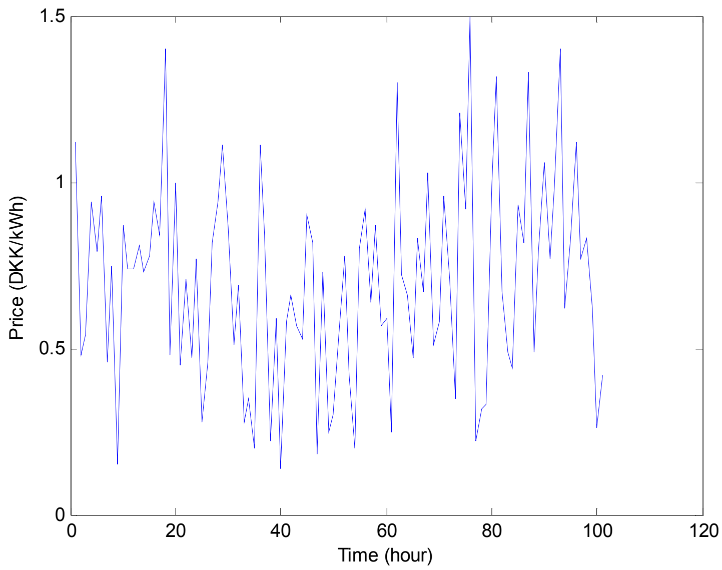

Figure 5-6: Electricity price posted by VPP for the first 100 hours of January 2006

Aggregated response

By applying the 7440 price signals to the prosumers in sequence, the response to the price variations of every individual prosumer under different context of demand can be found. According to the proposed operation scheme, the VPP observe the aggregated response at the end of each hour as shown in **Figure 5-7** and use this information as the input to its identification model.

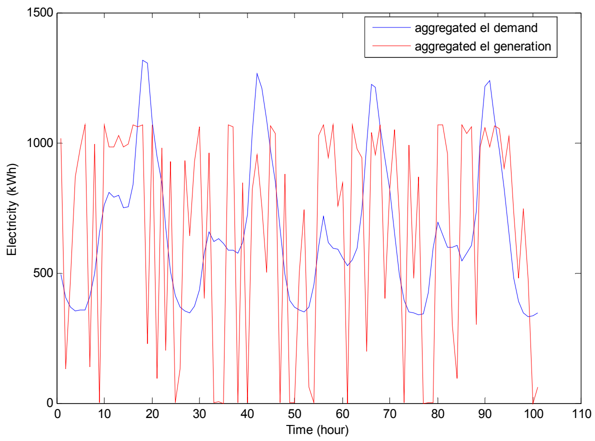

Figure 5-7: Aggregated generation and demand for the first 100 hours of January 2006

5.3.2 Identifying the price responsiveness with Artificial Neural Network

To identify the dynamic price responsiveness of the 100 prosumers, an **A**rtificial **N**eural **N**etwork (ANN) with three layers is used as the identification tool. The input-out data for identification are collected from the simulation run in section 5.3.1 and the **B**ack

Propagation (BP) training method is used to adjust the weights between neurons. The goal is to find the appropriate values for the weights that minimize the **R**oot **M**ean **S**quare (RMS) error between the identification data and the output of the network. This kind of networks has been claimed quite powerful in solving complex problems. For instance, a network of two layers, where the first layer is sigmoid and the second layer is linear can be trained to approximate any function (with a finite number of discontinuities) arbitrarily well. For more information about the BPNN and the notations given in **Figure 5-8**, one can read [w14]. The NN toolbox of Matlab 2009a is used to implement this study.

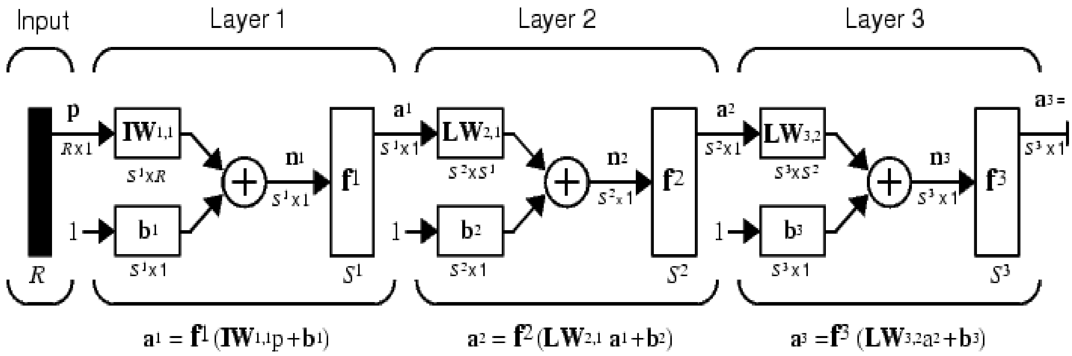

Figure 5-8: Architecture of a three-layer BPNN

Preparing the training data set

The original training samples collected from the simulation run in section 5.3.1 consists of 7440 pairs of four-element input vectors $u(t) = \{\pi_e(t), \pi_f(t), h_{d,vpp}(t), e_{d,vpp}(t)\}$ and single-element target vectors $y(t) = \{e_{g,vpp}(t)\}$. As the aggregated generation of prosumer group can be characterized as a modified autoregressive function as given in (5.4), the collected samples used for training the NN have to be reorganized.

$$y(t) = f(y(t-1), y(t-2), \dots, y(t-k), u(t), u(t-1), \dots, u(t-k)) \tag{5.4}$$

In this case, the number of time delay k is chosen as 2 after carrying out a number of test trials, which results in a reasonable accuracy level for identifying the price responsiveness of this prosumer group. As a result, the final input vectors of the BPNN is formulated as 7438 ninteen-element vectors $\{u(t), u(t-1), u(t-2), y(t-1), y(t-2)\}$; while the output vectors are formulated as 7438 single-element target vectors $\{y(t)\}$. In other words, provided the information about how the prosumer group responds to the posted prices in the previous three hours, the trained BPNN will be able to characterize the price responsiveness of the same group based on any forecasted demand profiles.

Constructing and training the BPNN

Because the computational performance of the NN is very sensitive to the number of layers and neurons, it is desirable to find appropriate NN structure. In [a54], Cybenko and Maren show that two hidden layers, whose neurons all use sigmoidal transfer functions, are sufficient to compute an arbitrary function of the inputs, and that a single hidden layer is sufficient for classification problems. Thus, in this case, a three-layer NN (two-hidden layer with one output layer) is constructed.

Choosing the number of neurons in the hidden layers is generally very difficult. The decision can be guided by theoretical and empirical limits. According to Hecht-Nielson's interpretation of the Kolmogorov theorem [b6][b7] , 2*N*+1 neurons (where *N* is the number of inputs) are necessary to calculate an arbitrary function. According to [a54], the optimum ratio between the first and the second hidden layer is three to one.

Such a NN is trained by using the Matlab function `'newfit'`, wherein the training algorithm Levenberg-Marquardt that is often the fastest back propagation algorithm to carry out supervised learning process. Transfer functions `'tansig'` and `'linear'` are used for the hidden layers and output layer respectively. As for the data division, 100% of the sampled data is used for training, 40% is used for validation and 40% is used for testing. To prevent overfitting, the maximum number of validation checks is chosen to be 6. Performance of this NN is measured by MSE, as given in (5.5).

$$MSE(y', y) = \frac{1}{N}\sum_{i=1}^{N}(y' - y) \qquad \textbf{(5.5)}$$

where y' is the estimated target value given by NN, and y is the real target value.

To more precisely determine the number of neurons for each hidden layer, the number of neurons is iteratively changed from 30 to 60 for the first hidden layer and from 10 to 20 for the second hidden layer. With each combination, the NN is trained 50 times to find the minimum MSE for entire input data sample. It is found when the number of neurons in the hidden layers is set 48 and 16 respectively, the minimum MSE 2.18. The overall training information is given in **Figure 5-9**, according to which the training stopped when the maximum number of validation failure is reached.

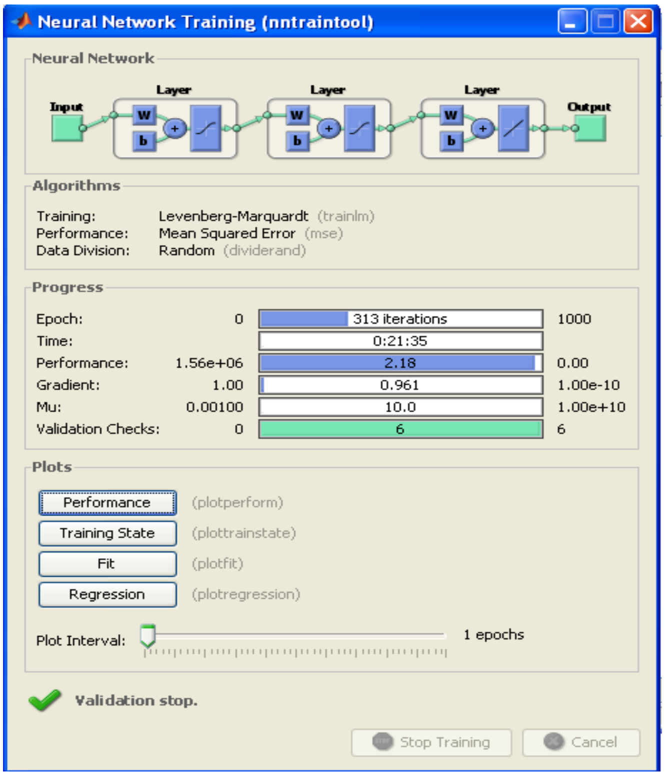

Figure 5-9: Information of training the NN

Testing the trained BPNN

To test the performance of the trained BPNN, the estimated price responsiveness of the prosumer group derived from the BPNN for both a single hour and a whole week are compared to the real values derived from the simulation module. Demand profile in this study is assumed to be perfectly forecasted.

For the intra hour price responsiveness, two cases have been tested: hour 3 and hour 44 in January, which are illustrated in **Figure 5-10** and **Figure 5-11** respectively. Initial conditions for the prosumer group are derived from the simulated prosumer group model where spot prices posted by VPP before that hour are assigned, and the VPP collects these response information at the end of each hour. Using the developed BPNN model, the VPP therefore tries to forecast the price responsiveness of the prosumer group for hour 3 and hour 44 in January respectively. Contrast to the real system price responsiveness, the VPP in these two cases all present relatively good estimations. Although the MSE values for both case relatively large, the MAPE[11] values are within 10%.

[11] According to the definition of MAPE $M = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{y-y\prime}{y}\right|$, when the actual value is zero, there will be a division by zero. Therfore, only non-zero values are included in the calculation of MAPE.

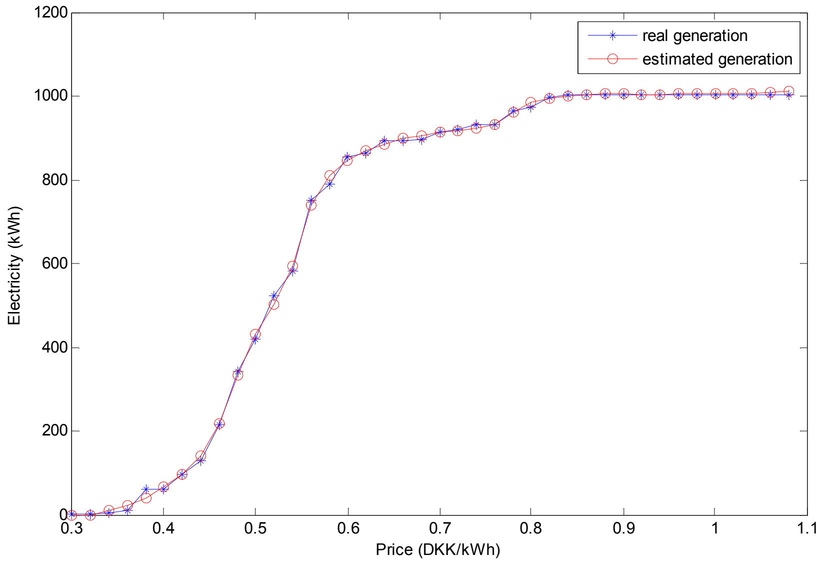

Figure 5-10: Testing the NN with varying prices for the 3rd hour of 1st day in 2006 (Initial 2 hours are assigned with real spot prices with MSE= 66.36, MAPE=0.082)

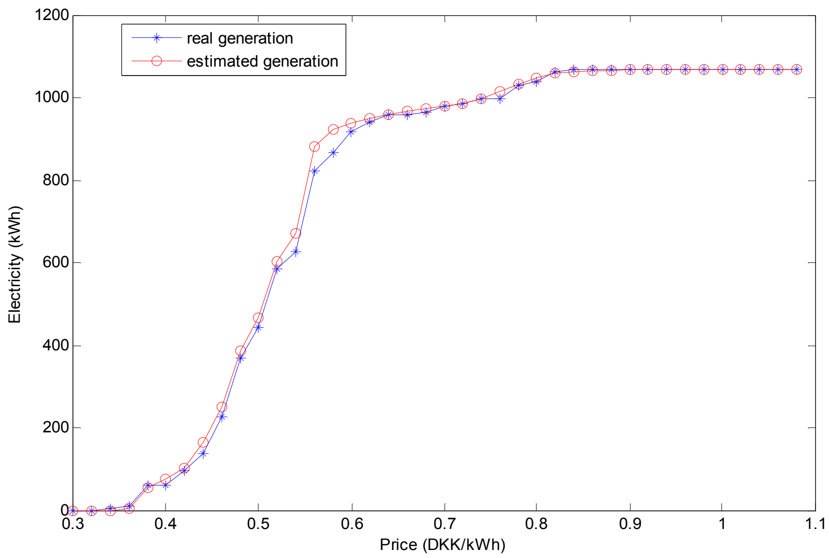

Figure 5-11: Testing the NN with varying prices for the 44rd hour in 2006
(Initial 42 hours are assigned with real spot prices with MSE=310.5, MAPE=0.063)

For the whole week examination, the real generation and estimated generation is compared for the 1st week in 2006. The estimated generation for hour *t* is again made on the basis of the real metered generation and demand values from hour *t-1* and hour *t-2* as well as the forecasted demand information for hour *t*. As given in **Figure 5-12**, the estimated values are fairly close to the real values, with the MAPE equals 0.073.

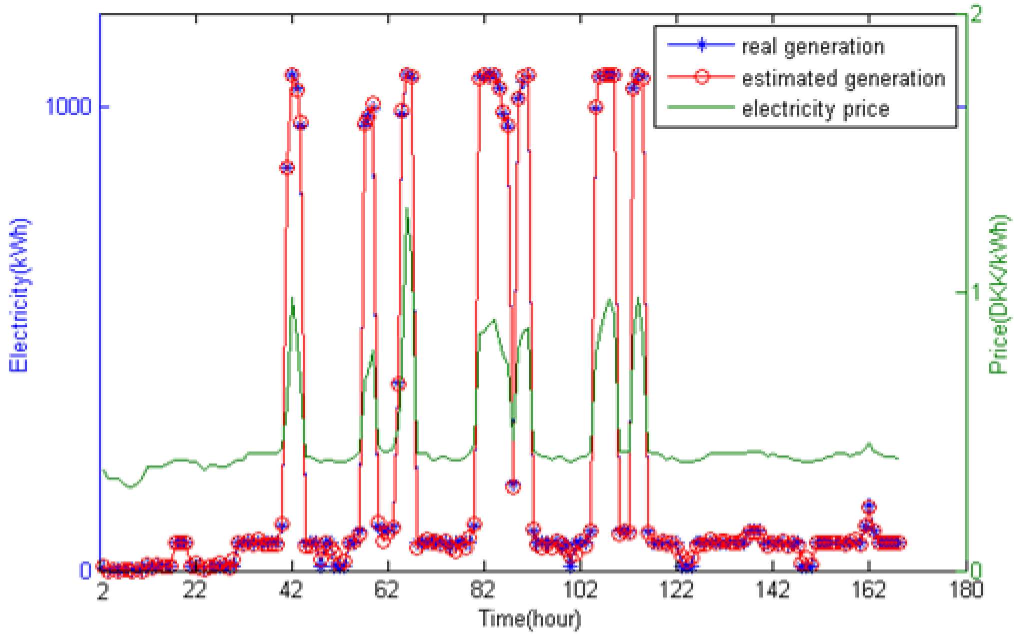

Figure 5-12: Testing the NN with real spot prices for the first week in 2006 (Initial 2 hours are assigned with real spot prices and MSE=43.41, MAPE=0.073)

5.3.3 Difficulty in finding the appropriate price signal

Based on the developed identification model, the VPP is able to estimate the price responsive characteristics of the prosumer group and post appropriate prices to regulate the production in order to get close to the desired values. However, the error introduced by estimation significantly challenges the VPP operator on choosing the appropriate prices. For instance, as shown in **Figure 5-13**, in case the VPP wants to have 820kWh generation for hour 44, it may post the price 0.58DKK/kWh in order to get the closest value. However, the actual generation will be 881.5kWh which requires the VPP to buy extra balancing power to eliminate this difference. Therefore, taking into account the negative effects of forecasting error, such as the extra balancing cost, will be the primary factor for VPP in deciding what the most appropriate price signal is.

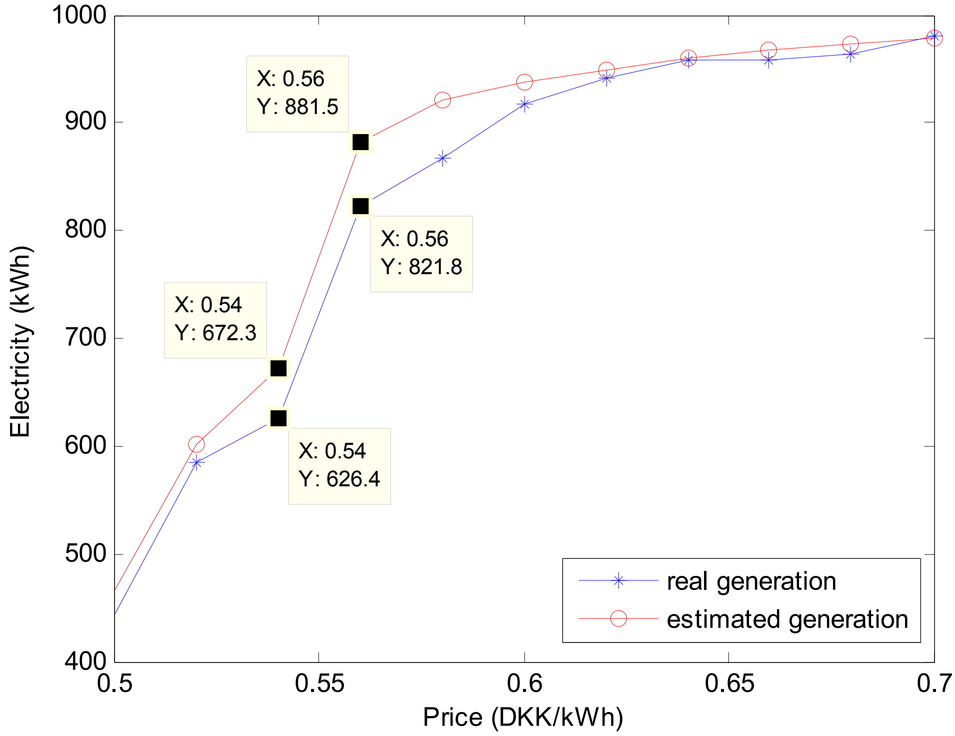

Figure 5-13: Real price responsiveness vs. the estimated price responsiveness for the 44rd hour in 2006 (enlarged from **Figure 5-14**)

One possible way to solve this problem can be adding a negotiation period process before publishing the real prices. As shown in **Figure 5-15** , the VPP first sends the estimated price to all prosumers and collect the generation schedules made by every customer. With the support of a closed-loop negotiation, the VPP finally finds out the electricity price for the according committed amount of power. This idea is simulated in [r15].

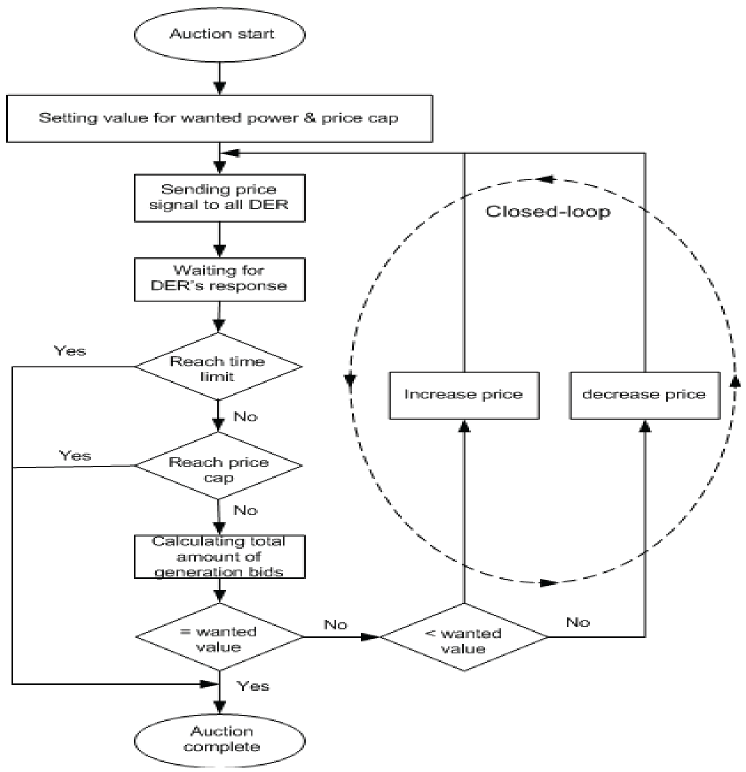

Figure 5-15: Flow chart illustrating how VPP initiate an auction with price-controlled scheme

Another problem resides with the discrete generation characteristics of the price-controlled VPP. In a special case where all the prosumers have the same µCHP systems installed, it can be observed that all the systems are almost on and off together due to the same marginal costs for all systems. In the simulated VPP with 100 µCHP systems, the diversity introduced by different system generation portfolio provides a relative wider regulating range. However, there are still relatively large gaps between the actual generation values for two adjacent prices. For instance, the actual generations can either be 881kWh or 672kWh but not in between. Unlike the direct controlled VPP, this obstacle can be a big problem for a small-scaled VPP. Hopefully, if the number of aggregated prosumer increases to thousands and different control logics are applied, the price based control may be able to achieve much smoother regulation.

5.4 Summary and discussions

In this chapter, the price signal controlled scheme for VPP is designed and simulated. The simulated prosumer group has a static generation pattern as each prosumer aims to optimize his hourly energy profile without recognizing the price pattern. Using the NN-based identification model, this pattern can be roughly recognized by VPP. However, since aggregated system information is used to train the NN, the error seems inevitable. This error can actually be reduced to a very small level when a single NN is trained to identify an individual prosumer as shown in **Figure 5-16**. Consequently, 100 NN can be developed separately to represent the 100 different prosumers and the estimated results are aggregated which clearly results in a much better forecasting power as shown in **Figure 5-17** compared to **Figure 5-12**. Although this may not be a feasible solution in practice since there may be a great number VPP participants and their generation pattern may keep changing; it clearly indicates that estimation may have to be done to various classes of prosumers rather than one class.

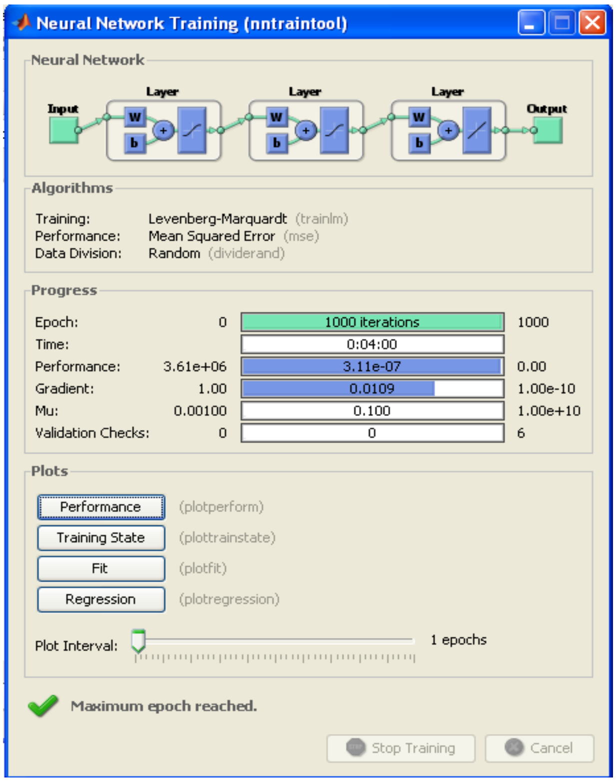

Figure 5-16: Information of training a single NN for one prosumer

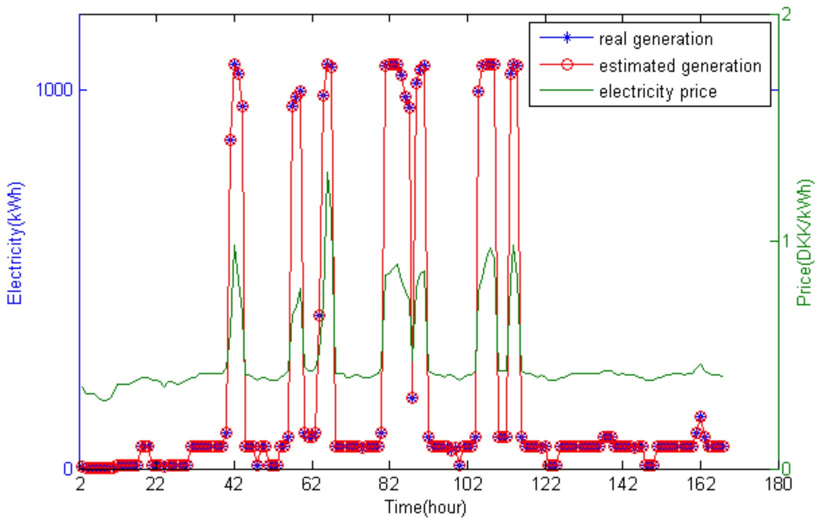

Figure 5-17: Testing the 100 aggregated NNs with real spot prices for the first week in 2006 (initial 2 hours are assigned with real spot prices and MSE=0.0023)

Further, for the simulated price controlled VPP, a large historical data sample is provided for identification purpose. Even though the VPP may be able to quickly build up his knowledge database by posting prices more frequently, such as 5 minutes, it may take a long time for the DER to adapt to the new tariff and respond appropriately. Thus in the case of using new tariff, with naive participants and naive energy trading agents like VPP, a double-complex set of adaption to the new scheme will take place. Participants will be learning and changing their behavior for given real-time prices at the very same time the VPP is trying to improve its guesses over their responses. Take this into consideration; posting price signals directly to the participants without receiving any confirmation from the participants will be rather risky for the early operation of price-controlled VPP since the unbalance is associated with the penalty cost.

Having a negotiation process before posting the final price may be one of the feasible ways to handle the uncertainties associated with price signal control. But it may negatively impact the participants' enthusiasm and bring in more trivial jobs for the participants, unless the HEMS are intelligent enough to replace the human decisions. Real life example for this kind HEMS can be found in [r5] where special controllers are developed to automatically correlate temperature with price signals according to a pre-defined program and bid in a 5 minute electricity market. Other designs, as given in [a55], use price droop which is similar to frequency droop to guarantee the stable price response. Nevertheless, to place the sort of price signal controllers into the customers' premises are not easy, since the pre-defined programs may not be able to fully represent the customers' willingness.

Another option for the VPP to handle the uncertainties can be using a combined operation scheme including both direct control and price-signal control. The price signal control scheme can be used to roughly control a large number of participants, and the direct control scheme can be used either to participate in the wholesale market regularly or to function as internal balancing resources to the VPP. In such case, the participants can voluntarily decide which scheme is better for their generation/usage patterns.

As stated above, solely price signal controlled VPP may not be a flawless solution, especially considering the difficulties in handling the uncertainties. The current market principle, where the real-time market price is actually post calculated, may have to account for this. However, it should be clear that price signal control is quite feasible. Using price signal control may be very challenging to parties like VPP, but can be a very positive solution for parties like TSO or large utilities to facilitate the integration of DER and to offer more efficient solutions on using of DER. Using frequency related price signal is a good sample over this aspect.

6 EXPERIMENTAL SETUP

CET has been working on an experimental setup for the VPP as a proof-of-concept. This prototyped VPP intends to provide a generic testbed for different control and communication schemes. In this chapter, the ongoing setup is briefly introduced. More details about the related theoretical study and software design can be found in [r16], wherein Anders and Einar elaborate on how the IEC 61850 standard, especially IEC61850-7-420, based communication is used for the experimental setup at CET.

6.1 Current setup

The architecture for the current experimental setup is shown in **Figure 6-1**. The DER devices involved in the current setup are two 5.0-5.5kWe ICE-based Dachs µCHP systems from SenerTec. One of the units runs on natural gas and the other one runs on diesel fuel. Both of them simply work in the on/off mode and provide no electrical modulation.

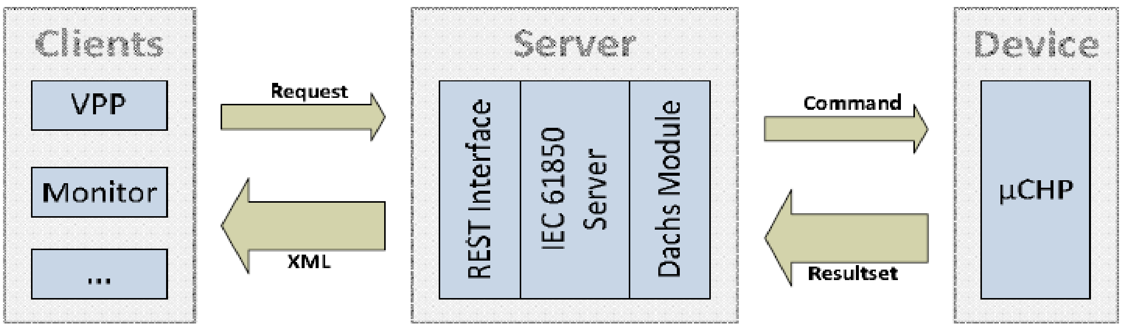

Figure 6-1: Architecture for the experimental VPP

In this prototype, the IEC 61850 server, as the core part, is written in C# for the .NET framework and implemented on an ordinary desktop computer. This IEC 61850 server contains all the logic needed to handle the IEC 61850 data model as well as manage the reporting and logging of the measured data.

The most commonly used protocol for the IEC 61850 standard is the **M**anufacturing **M**essage **S**pecification (MMS) protocol. This binary protocol is good in terms of performance but makes prototyping and debugging much harder as the messages are not humanly readable [a56]. To avoid buying one of the expensive existing server implementations and to test web services as communication mappings, the experimental server is implemented with **RE**presentational **S**tate **T**ransfer (RESTful) interface which handles all communication with the clients.

The Dachs module, which is depicted in **Figure 6-1**, is developed under a plug-in framework. Under this framework, any type of the DER devices supported by the IEC 61850 can be connected through the specific device module e.g. Dachs module, EV module, etc. The Dachs module handles the communication with the physical Dachs µCHP systems. The information of the systems such as on/off status, power output, etc. is collected via the manufacture provided RS232 serial communication interface. This information is further mapped to the **U**niform **R**esource **L**ocator (URL) format using the RESTful web services, which can be reached by the VPP client almost anywhere through the internet.

Communication between the VPP and the DER is setup using a secure tunnel, as shown in **Figure 6-2**. Although there are other possible ways such as dedicated communication lines which can be used to meet the communication requirement, the secure tunnel seems to be the most convenient way to implement such communication considering the restrictions in the DTU PowerLab and system costs.

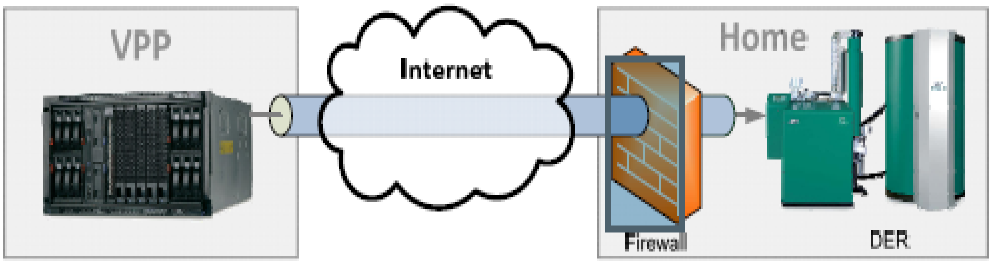

Figure 6-2: Communication tunneled for the present experimental setup

The operation panel of the VPP is currently under construction. Instead, a helpful **G**raphical **U**ser **I**nterface (GUI) shown in **Figure 6-3** has been developed to remotely monitor the µCHP system. Anyone who has access to the interface can remotely turn on and turn off the µCHP systems. This demonstrates the direct controlled operation scheme of VPP.

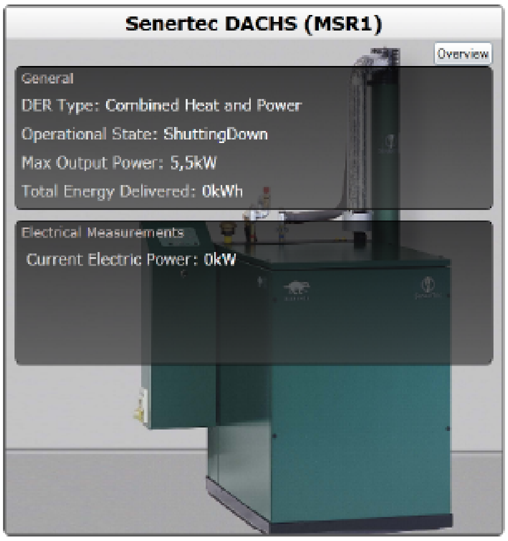

Figure 6-3: Screenshot showing the GUI for the SenerTec Dachs µCHP system

6.2 Future development

The future development of the present VPP prototype will be made in collaboration with the research team of the Danish EDISION project also from CET, since the EVPP concept is no other than a MBVPP with specific focus on EV aggregation. As shown in **Figure 6-4**, functions such as forecasting, scheduling and controlling, etc. will be further developed and embedded in it. Already available resources at CET, like the Citroen C1 EV, XRGI15 µCHP system and battery system will be successively connected to the VPP testbed. Different control schemes, from direct control to price signal control, will be tested for both real DER and simulated devices.

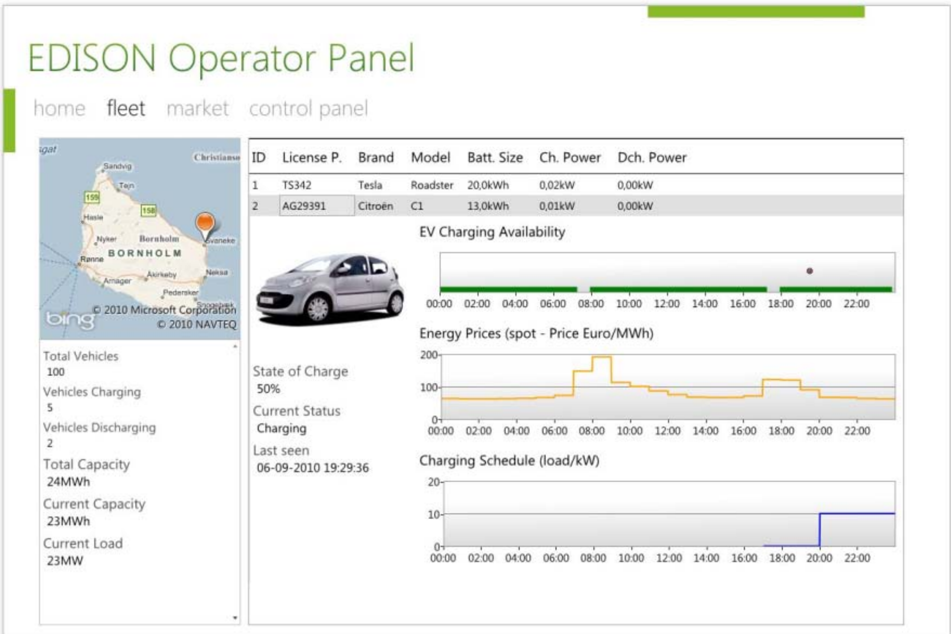

Figure 6-4: Operation panel of EVPP

7 CONCLUSIONS AND FUTURE WORK

This thesis explored the innovative concept of Virtual Power Plant focusing on how to facilitate the DER integration under present regulatory framework. The main outcome of this study is the clarification of different VPP concepts, the generic market-based design which changes the operation of DER from "passive" into "active", the investigation of different control schemes for market-based VPP applications and the setup of a prototyped VPP at the CET laboratory. Regarding these aspects and the associated challenges, this chapter highlights a number of key points resulted from this study and recommends several topics for future work.

7.1 Conclusions

In section 1.2, four problems statements were outlined for the project. In the following, the results are given.

1. What is the VPP and what is the state of the art of VPP?

Based on the intensive review presented in Chapter 2, the VPP studied in this research project is defined as an entity/energy management system that aggregates multi-fuel, multi-location and possibly multi-owned DER units via advanced ICT infrastructure either for the purpose of energy trading or to provide system support services.

Due to its potential benefits, the VPP concept has been widely developed and used in recent years. These developments differ from each other in aggregation needs, obligations, control requirements and communication requirements. In addition to the preference for centralized control, market-based operation seems to be a task granted with higher priority than the others.

2. How to develop a generic VPP concept which benefits all parties?

The market-based design introduced in chapter 3 clarifies the generic objective that every VPP may have to meet: to efficiently participate in the electricity market. By placing the VPP in the marketplace, the present "fit and forget" operation of DER is replaced by the active participation in the electricity market. Moreover, the market participation can provide multiple value streams for the VPP due to the possibility of multiple services provision. This in turn benefits the parties who are in need of the corresponding services.

To increase the flexibility of the MBVPP, a set of functional modules are developed. Depending on the local contexts, these functional modules can be plugged in and out to meet different design requirements.

3. How can the VPP efficiently control/coordinate the operation of the DER?

The control/coordination algorithms developed for market-based VPP differ from each other in terms of control structure, information volume and uncertainties faced when making decisions. Two control schemes: direct control and price signal control have been studied in this thesis. In both cases, the simulated VPP function as an energy supplier which aggregates the prosumers. However, as no elasticity has been assigned to the demand side, there is no essential difference between aggregating the prosumers and aggregating the DER.

Direct controlled VPP offers the best power in controlling the aggregated DER. The simulated direct controlled VPP actually functions completely the same way as a conventional energy supplier in terms of making the best use of the given generation portfolio based on the available market information. The optimization approach proposed for the direct controlled VPP is a very generic method which can be applied to the VPP with very different generation portfolios. The model for the µCHP system and the proposed least cost operation is suitable for making the cost and benefit analysis on hourly basis. They can also be adjusted to simulate more precise responses of the µCHP systems if the market information or the demand information is provided on shorter time intervals.

Price signal controlled VPP proposed in this thesis offers probably the most attractive services to the DER as the price is posted in advance of the electricity delivery. This kind of control provides advantages in its scalability and simplicity; however, the associated risk faced by the VPP is more significant than what a direct controlled VPP faces. Although the identification tool developed using NN makes a relatively good estimation, in real life the continuous varying generation/demand pattern of smart DER may be very hard to be captured. This can become much worse when limited historical data is available. Therefore, alternative solution such as adding a negotiation period in advance of posting the electricity prices has been proposed. Still, this solution has drawbacks on heavier communication load and may also be burdensome to the DER participants.

4. How to implement and test the proposed MBVPP concept in a real life?

The experimental setup at CET demonstrates a direct controlled VPP. The generic communication interface developed according to IEC-61850-7-420 standard offers a good example for VPP applications with the standardized protocol. Current setup allows for the remote monitoring and on/off control of the SenerTec Dachs µCHP units.

In addition to the above statement, it has been shown that the VPP is quite feasible to be implemented without obvious technical barriers if an advanced ICT infrastructure is available. Both the DER owners and the other parties involved in power system operation can benefit from the market participation of VPP. The µCHP systems, due to their controllability, are suitable for direct controlled schemes. In the case of price signal controlled VPP, the modeled µCHP group shows difficulty in providing smooth and continuous power. This is mainly due to the lack of the DER diversity and the price responsiveness of the simulated generation characteristics for the µCHP systems.

7.2 Future work

The idea of VPP is an interesting subject where a lot of research needs to be done. Below, some topics are outlined as proposals for future work.

- Contractual relationship between the DER and the VPP has to be taken good care of to realize the values of different DER technologies and solve the problems related to profit distribution (especially under direct control schemes), multiple services provision and imbalance settlement, etc.

- In the future, the number of VPP-like market participants may increase. Their participation thus has potential impacts on both the electricity prices and the costs for grid support services. To study these impacts is very useful for all market participants and the market operators.

- As the currently simulated VPP operates on hourly basis with only µCHP systems, simulations for the VPP with more diversified DER portfolio on much shorter time intervals e.g. 5minutes will be helpful to carry out more detailed cost-benefit analysis especially in the context of entering the real-time market and the ancillary service market.

- When price signal control scheme is used, a multi-criteria model for estimating the price responsiveness of the DER may be required instead of only using the statistical measures such as MAPE or MSE, etc. This is due to the fact that the deviations between the real values and the estimated values lead to imbalance cost. Thus, the prognosis that results in low cost of the consequences of prognosis errors may also have to be taken into account.

- Having a combined control scheme such as price signal control and direct control function together in one VPP may be one feasible solution to mitigate the downsides of the price signal control. Thus, it is interesting to make this study to analyze the related issues, such as how many DER should be direct controlled to mitigate the uncertainty level caused by the price signal controlled DER.

- In order to complete the feasibility study of the VPP applications, the investment and operational cost of ICT should also be investigated. The pros and cons of different communication strategies are also worthwhile studying to facilitate the cost effective design of the VPP.

- Continuation of the present experimental setup is already on the agenda. A full scaled VPP prototype with more types of DER devices and a set of market-based functional modules will be constructed and demonstrated in the near future.

8 REFERENCES

Articles:

[a1] B. Fesmire, ABB Inc. *Energy Efficiency in the Power Grid*, Renwable Energy Network, July, 2007

[a2] N. Hatziargyriou, H. Asano, R. Iravani, and C. Marnay. *Microgrids: an overview of ongoing research development, and demonstration projects*. IEEE Power & Energy Magazine, pp.78-94, July, 2007,

[a3] J.A. P. Lopes, N. Hatziargyriou, J. Mutale, P. Djapic, and N. Jenkins. *Integrating distributed generation into electric power systems: a review of drivers, chanllenges and opportunities*. Electric Power Systems Research, Vol. 77, Issue 9, July 2007

[a4] M.Braun, P. Strauss. *A Review on Aggregation Approaches of Controllable Distributed Energy Units in Electrical Power Systems*. International Journal of Distributed Energy Resources, Vol. 4, Issue 4, pp.297-319, 2008,

[a5] K. Takahiro, *Development Strategies toward Promotion and Expansion of Residential Fuel Cell Micro-CHP System in Japan*, Osaka Gas Co., Japan 2008.

[a6] *EU Directive 2004/8/CE*, Official Journal of the European Union, 2004

[a7] COGEN, *Small-scale CHP Factsheet Denmark*, 2007

[a8] M. Naslund and J. D. Wit, *Residential Fuel Cell Micro Cogeneration- Opportunities and Chanllenges in the Systsem Design*, International Gas Union Research Conference, Paris, 2008

[a9] *California Distributed Energy Resources Guide*

[a10] L. Kojovic, *Impact of DG and Voltage Regulator Interaction on Distribution System Voltage Regulation*, 17^{th} International Conference on Electricity Distribution, Barcelona, 2003

[a11] R.Madlener, M.Kaufmann, *Power exchange spot market trading in Europe: theoretical considerations and empirical evidence*, OSCOGEN, Deliverable 5.1b,

[a12] S. You, C. Træholt, B. Poulsen, *A Market-Based Virtual Power Plant*, Proceedings of International Conference on Clean Electrical Power, Capri, Italy, 2009

[a13] P.B. Andersen, B. Poulsen and M. Decker, *Evaluation of Generic Virtual Power Plant Framework Using Service Oriented Architecture*, 2nd IEEE International Conference on Power and Energy, December, 2009

[a14] F. Ygge and H. Akkermans, *Decentralized Markets versus Central Control: A Comparative Study*, Journal of Artificial Intelligence Research Vol.11, pp. 301-333, 1999

[a15] H. Voos, *Market-based control of complex dynamic systems*, Proceedings of the IEEE International Symposium on Intelligent Control ISIC'99, Cambridge (MA), 1999.

[a16] I.G. Kamphuis, J.K. Kok, C.J.Wamer, *Massive Coordination of Residential Embedded Electricity Generation and Demand Response using Power Matcher Approach*, EEDAL, 2006

[a17] H. Akkermans, J. Schrenemarkers, K. Kok, *Microeconomic Distributed Control: Theory and Application of Multi-agent Electronic Markets*, CRIS, 2004

[a18] J.K. Kok, C.J. Warmer, I.G. Kamphuis, *PowerMatcher: Multiagent Control in the Electricity Infrastructure*, International Conference on Future Power Systems, 2005

[a19] R. Caldon, A.R.Patria, R. Turri, *Optimization Algorithm for a Virtual Power Plant Operation*, UPEC, 2004

[a20] R. Caldon, A.R. Patria, R. Turri, *Optimial Control of a Distribution System with a Virtual Power Plant*, Bulk Power System Dynamics and Control, Italy, 2004

[a21] F.Bignucolo, R.Caldon, V. Prandoni, *The Voltage Control on MV Distribution Networks with Aggregated DG Units (VPP)*, UPEC 2006

[a22] B. Roossien, M. Hommelberg, C.Warmer, *Virtual Power Plant Field Experiment using 10 Micro-CHP Units at Consumer Premises*, CIRED Seminar 2008: SmartGrids for Distribution

[a23] P. E. Morthorst, *The effect of Wind Power on Spot Market Prices*, EWEC 2007 Brussels

[a24] S. You, C. Træholt, B. Poulsen, *A Study on Electricity Export Capability of the µCHP System with Spot Price*, IEEE PES 2009 General Meeting, 2009, Calgary, Alberta, Canada

[a25] S. You, C. Træholt, and B. Poulsen, *Generic Virtual Power Plants: Management of Distributed Energy Resources under Liberalized Electricity Market*, The 8th IET International Conference on Advances in Power System Control, Operation and Management, 2009, Hong Kong, P.R. China

[a26] A.D. Hawkes and M.A.Leach, *Cost-effective operating strategy for residential micro-combined heat and power*, Energy,Vol.32, Issue 5, pp.711-723, May 2007

[a27] A.D. Peakcock and M.Newborough, *Impact of micro-CHP systems on domestic sector CO_2 emissions.* Applied Thermal Engineering, Vol.25, Issue 17-18, pp.2653-2676, December 2005

[a28] A.D. Peakcock and M.Newborough, *Impact of micro-combined head and power systems on energy flows in the UK electricity supply industry*. Energy, Vol.31, Issue 12, pp.1804-1818, Septermber 2006

[a29] M. Newborough, *Assessing the benefits of implementing micro-CHP systems in the UK. Journal of Power and Energy*, Vol.218, Issue 4, pp203-218, August 2004

[a30] A. Ferguson, N, Kelly, *Modelling residential-scale combustion-based cogeneration in building simulation*, Journal of Building Performance Simulationg, Vol.2, Issue 1, pp1-14, March 2009

[a31] K.R. Voorspools, W.D. Dhaeseleer, *The evaluation of small cogeneration for residential heating*, International Journal of Energy Research, Vol.26, Issue 13, pp1175-1190

[a32] H.i. Onovwiona, V.I. Ugursal and A.S. Fung, *Modeling of internal combustion engine based cogeneration systems for residential applications*, Applied Thermal Engineering, Vol.27, Issue 5-6, pp. 848-861, April 2007

[a33] B.Bogner, S.S.Abildgaard and J.R.Andersen "*Power Distribution System*," UK. Patent GB2402001, Sep. 20, 2006.

[a34] A.D. Hawkes and M.A.Leach. *Impacts of temporal precision in optimization modeling of micro-combined head and power*, Energy, Vol.30, Issue 10, pp1759-1779, July 2005

[a35] A.D. Peakcock and M.Newborough, *Controlling micro-CHP systems to modulate electrical load profiles*, Energy, Vol.32, Issue 7, 1093-1103, July 2007

[a36] Technical Documentation of SENERTEC CHP unit

[a37] Personal communication with the EC Power/AS specialists

[a38] Design Guide for EC Power/AS micro-CHP system

[a39] Denmark: Internal Market Fact Sheet 200

[a40] M.Braun, *Virtual Power Plant functionalities: demonstrations in a large laboratory for distributed energy resources*, 20th International Conference on Electricity Distribution, Prague 2009

[a41] D.Faille, C.Mondon, and L. Henckes. *Modeling and optimization of a micro combined head and power plant*, In Proceedings of the 16th IFAC World Confress, Prague, July 2005

[a42] D.Faille, C.Mondon, and B. Al-Nasrawi, *mCHP optimization by dynamic programming and mixed integer linear programming*. In proceedings of the 14th International Conference on Intelligent Systems Applications to Power System-Kaohsiung, Taiwan, November 2007

[a43] H. Glavitsch and F.L. Alvarado, *Management of multiple congested conditions in unbundled operation of a power system,* IEEE Transactions on Power Systems, Vol.13, Issue 3, pp.1013-1019,1998

[a44] F.L. Alvarado, J. Meng, C.L. DeMarco, and W.S. Mota, *Stability analysis of interconnected power systems coupled with market dynamics*, IEEE Transactions on Power Systems, Vol 16, Issue 4, pp. 695-701,2001

[a45] F.L. Alvarado, *Is system control entirely by price feasible?* Proceedings of the 36th Annual Hawaii International Conference on System Sciences, Big Island, Hawaii, 2003

[a46] F.L. Alvarado, *Controlling power systems with price signals*, Decision Support Systems, Vol. 40, Issue 3-4, pp.495-504, 2005

[a47] C.L. Tseng, G.Barz, *Short-term generation asset valuation: a real options approach*, Operation Research, Vol. 50. No. 2, March-April 2002, pp.297-310

[a48] S.Chanana, A.Kumar, *A price based automatic generation control using unscheduled interchange price signals in Indian electricity system*. International Journal of Engineering, Science and Technology, Vol 2, No.2, 2010, pp.23-30

[a49] A.Fqruqui, S.S.George, *The value of dynamic pricing in mass markets,* The Electricity Journal, Vol.15, Issue 6, 2002

[a50] K. Herter, *Residential implementation of critical-peak pricing of electricity*, Energy Policy, Vol.35, Issue. 4, pp. 2121-2130, April 2007

[a51] T. N. Taylor, *24/7 Hourly response to electricity real-time pricing with up to eight summers of experience*, Journal of Regulatory Economics, Vol.27, Issue.3, 2005

[a52] S. You, C. Træholt, B. Poulsen, *Is micro-CHP Price Controllable under Price Signal Controlled Virtual Power Plant*, Accepted by the 4th IASTED Asian Conference on Power and Energy Systems, 2010, Thailand

[a53] J.D.Wit, *Implementation of micro CHP in single-family houses*, 23rd World Gas Conference, Amsterdam 2006

[a54] H.N. Robert, "*Kolmogorov's Mapping Neural Network Existence Theorem*," in Proc. Int. Conf. Neural Networks (San Diego 1987), vol. 3, pp.11-14, IEEE Press, New York.

[a55] J.B.Cardell, *Distributed Resource Participation in Local Balancing Energy Markets*, Power Tech, IEEE Lausanne,2007

[a56] A. B. Pedersen, E. B. Hauksson and P.B. Andersen, "*Facilicating a generic communication interface to distributed energy resources: Mapping IEC 61850 to RESTful services*", to be published in the Proceedings of International Conference on Smart Grid Communications, 2010, USA

Books:

[b1] **Distributed Generation: A Nontechnical Guide**, A. Chambers, B.Schnoor and S. Hamilton, Pennwell Books, February 15, 2001

[b2] **Micro Cogeneration: Towards Decentralized Energy Systems**, M. Pehnt, M. Cames, and C. Fischer, Springer, 2005

[b3] **Securing Electricity Supply in the Cyber Age: Exploring the Risks of Information and Communication Technology in Tomorrow's Electricity Infrastructure**, Z. Lukszo,Springer, 2010

[b4] **Wind Power in Power Systems**, edited by Thomas Ackermann, John Wiley & Sons, Ltd (UK), pp. 36.

[b5] **Spot Pricing of Electricity,** Fred C. Schweppe, Michael C.Caramanis, Richard D. Tabors and Roger E.Bohn, published by Kluwer Academic Publishers, Fourth Printing 2000.

[b6] **Neurocomputing**, Rober Hecht-Nielsen, published by Addison-Wesley Longman Publishing Co., 1989

[b7] **Handbook of Neural Computing Applications,** A. Maron, C. Hmt & R. Pap, Academic Press Inc., San Diego, CA 1990.

Reports:

[r1] WADE, World Survey of Decentralized Energy 2006

[r2] California Energy Commission: Integration of Distributed Energy Resources-The CERTS MicroGrid Concept, 2003

[r3] Pike Research, Microgrids: Islanded Power Grids and Distrbuted Generation for Community, Commerical and Institutional Application, 2009

[r4] Carbon Trust, Micro-CHP Accelerator, 2007

[r5] D.J. Hammerstrom, Pacific Northwest GridWise Testbed Demonstration Projects: Part I. Olympic Peninsula Project

[r6] Z.Xu, J.Østergaard and M.Togeby, Demand as Frequency Controlled Reserve: Final report of the PSO project

[r7] Ea Energy Analyses, 50% Wind Power in Denmark in 2025 – English Summary, 2007

[r8] European Virtual Fuel Cell Power Plant Management Summary Report,

[r9] Nordel, Description of Balance Regulation in the Nordic Countries,

[r10] FC+COGEN-SIM, Performance Assessment of Residential Congeneration Systems in different Italian climatic zones,

[r11] S. Borenstein, M. Jaske, Dynamic Pricing, Advanced Metering, and Demand Response in Electricity Markets,

[r12] G.Barbose, C.Goldman, A survey of utility experience with real-time pricing, Berkeley CA, Lawrence Berkeley National Laboratory, LBNL-54238

[r13] S. Borenstein, M. Jaske, Dynamic Pricing, Advanced Metering, and Demand Response in Electricity Markets

[r14] G.Barbose, C.Goldman, *A survey of utility experience with real-time pricing*, Berkeley CA, Lawrence Berkeley National Laboratory, LBNL-54238

[r15] K. Boussoufa, Control of generic virtual power plant, master thesis, DTU, 2008

[r16] A. B. Pedersen and E.B.Hauksson, Enabliing distributed energy resources in a virtual power plant using IEC 61850, master thesis, DTU, 2010

[r17] International Energy Agency, Hybrid and electric vehicles: The electric drive establishes a market foothold, 2009

Websites:

[w1] http://www.epa.gov/climatechange/emissions/co2_human.html

[w2] http://www.cityplan.cz/index.php?id_document=1134

[w3] http://www.electricitystorage.org/ESA/technologies/

[w4] http://www.energy.ca.gov/distgen/

[w5] http://www.control4.com/

[w6] http://www.fenix-project.org/

[w7] http://www.edison-net.dk/

[w8] http://www.siemens.com/innovation/en/publikationen/pof_fall_2009/energie/virtkraft.htm

[w9] http://www.nordel.org/

[w10] http://www.delta-ee.com/downloads/Delta_Micro-CHP%20Annual%20Sales_jul10.pdf

[w11] http://www.ecpower.co.uk/index.php?option=com_content&view=article&id=120&Itemid=104

[w12] http://www.energinet.dk/en/menu/Market/Download+of+Market+Data/Download+of+Market+Data.htm

[w13] http://www.ieso.ca/imoweb/pubs/consult/mep/LMP_NodalBasics_2004jan14.pdf

[w14] http://www.mathworks.de/access/helpdesk/help/pdf_doc/nnet/nnet.pdf

A DOMESTIC DEMAND PROFILES

The average hourly electricity demand and heat demand distribution across 2006 for Danish multi-family houses is given in **Figure A-1** and **Figure A-2** respectively. As the annual energy consumption for this type of house is typically around 4.8MWh for electricity and 13MWh for heat [a53], the hourly demand profile for a typical Danish multi-family house can be derived.

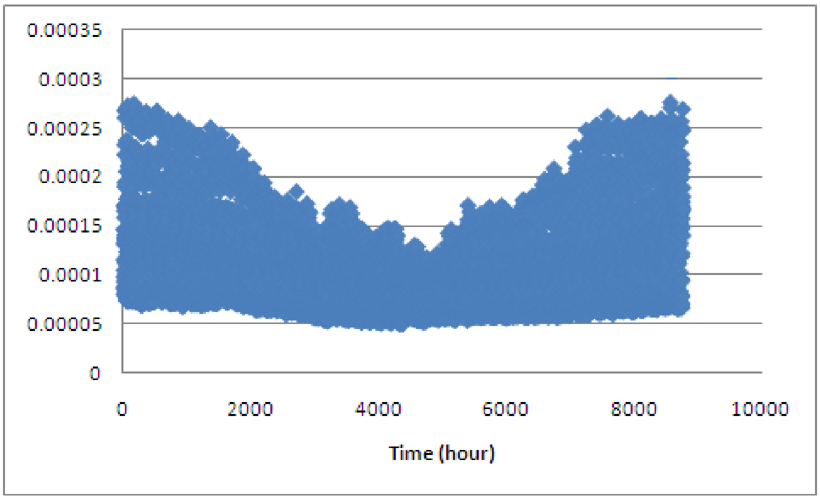

Figure A-1: Distribution of electricity demand for a Danish multi-family house in 2006

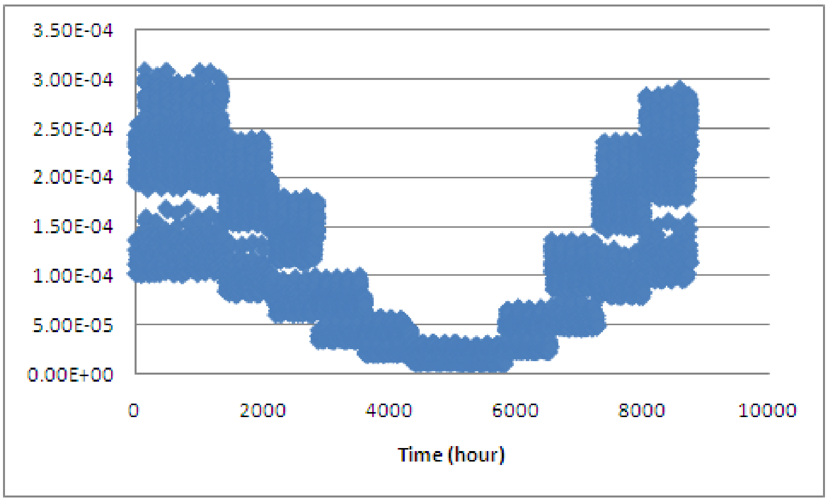

Figure A-2: Distribution of heat demand for a Danish multi-family house in 2006

In **Figure A-3**, the demand for the first three days (as a reference) of January is shown, provided the above annual energy consumption values.

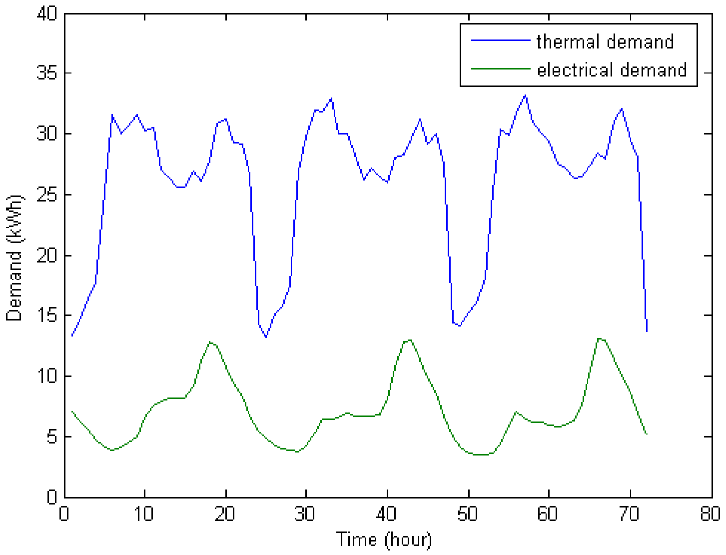

Figure A-3: Average demand profile of a Danish multi-family house for the first three days of January 2006

In order to randomly generate multiple demand profiles (100 in this case) representing a number of Danish family houses, a normal distribution of the generated demand profiles in every hour is assumed. For every hour, the mean value of the normal distribution is set equal to the referenced average value and the standard deviation is set to 0.1. **Figure A-4** gives an example for the generated demand profiles.

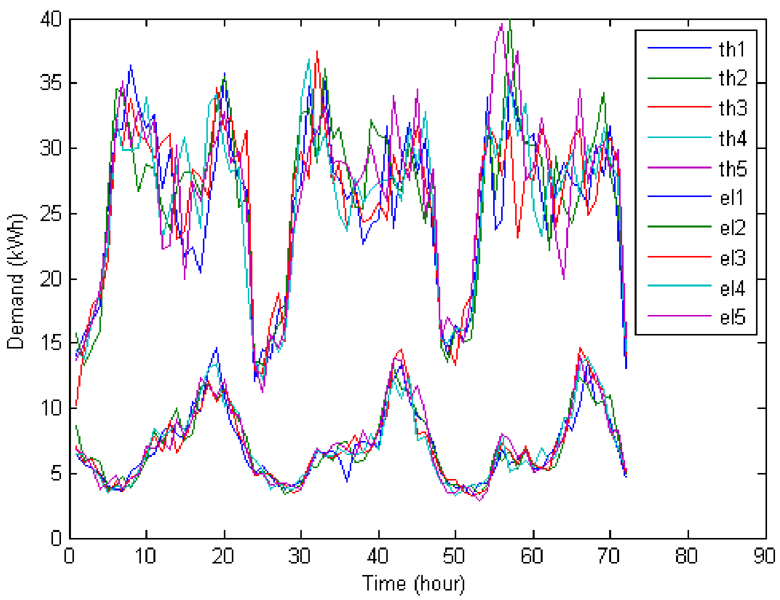

Figure A-4: Five of the generated Danish multi-family house demand profiles for the first three days of January 2006

B GENERATION PORTFOLIOS FOR 100 µCHP SYSTEMS

The µCHP systems are modeled with linear generation characteristics. System 1 to system 25 represent the ICE-based XRGI15 µCHP units; system 26 to system 50 represent the ICE-based XRG13 µCHP units; sytem 51 to system 75 represent the ICE-based DACHS µCHP unit from Senertec and the last 25 systems represent the PEMFC-based µCHP systems. The electricity production from the first 50 EC Power units can be modulated within in the given range and the DACHS units can only work in the on/off mode. As for the PEMFC-based µCHP units, it is assumed the electricity can be modulated between 0-9kWe with constant electrical efficiency at 40% and thermal efficiency at 50%. All units are assumed to run on natural gas. For the PEMFC-based µCHP unit, the natural gas is burnt to generate hydrogen through a reformer, which produces electricity in the end.

Table B-1: Generation portfolio for the prosumer group

System	a_1	b_1	a_2	b_2	e_{min}(kW)	e_{max}(kW)	h_{smax}(kWh)	η_b
1	1.4	8.5	2.6	10.3	6	15.2	8.4	0.81
2	1.4	8.5	2.6	10.3	6	15.2	16.8	0.81
3	1.4	8.5	2.6	10.3	6	15.2	11.2	0.77
4	1.4	8.5	2.6	10.3	6	15.2	22.4	0.78
5	1.4	8.5	2.6	10.3	6	15.2	8.4	0.8
6	1.4	8.5	2.6	10.3	6	15.2	22.4	0.77
7	1.4	8.5	2.6	10.3	6	15.2	22.4	0.83
8	1.4	8.5	2.6	10.3	6	15.2	22.4	0.77
9	1.4	8.5	2.6	10.3	6	15.2	22.4	0.77
10	1.4	8.5	2.6	10.3	6	15.2	8.4	0.77
11	1.4	8.5	2.6	10.3	6	15.2	16.8	0.77
12	1.4	8.5	2.6	10.3	6	15.2	11.2	0.79
13	1.4	8.5	2.6	10.3	6	15.2	11.2	0.78
14	1.4	8.5	2.6	10.3	6	15.2	22.4	0.84
15	1.4	8.5	2.6	10.3	6	15.2	22.4	0.79
16	1.4	8.5	2.6	10.3	6	15.2	11.2	0.77
17	1.4	8.5	2.6	10.3	6	15.2	16.8	0.84
18	1.4	8.5	2.6	10.3	6	15.2	8.4	0.85
19	1.4	8.5	2.6	10.3	6	15.2	11.2	0.79
20	1.4	8.5	2.6	10.3	6	15.2	22.4	0.76

21	1.4	8.5	2.6	10.3	6	15.2	11.2	0.78
22	1.4	8.5	2.6	10.3	6	15.2	16.8	0.79
23	1.4	8.5	2.6	10.3	6	15.2	11.2	0.81
24	1.4	8.5	2.6	10.3	6	15.2	11.2	0.78
25	1.4	8.5	2.6	10.3	6	15.2	8.4	0.81
26	1.3	11.8	2.5	15	4	13	16.8	0.82
27	1.3	11.8	2.5	15	4	13	16.8	0.77
28	1.3	11.8	2.5	15	4	13	16.8	0.76
29	1.3	11.8	2.5	15	4	13	16.8	0.78
30	1.3	11.8	2.5	15	4	13	8.4	0.78
31	1.3	11.8	2.5	15	4	13	16.8	0.79
32	1.3	11.8	2.5	15	4	13	8.4	0.8
33	1.3	11.8	2.5	15	4	13	8.4	0.76
34	1.3	11.8	2.5	15	4	13	16.8	0.78
35	1.3	11.8	2.5	15	4	13	8.4	0.83
36	1.3	11.8	2.5	15	4	13	16.8	0.75
37	1.3	11.8	2.5	15	4	13	11.2	0.84
38	1.3	11.8	2.5	15	4	13	8.4	0.82
39	1.3	11.8	2.5	15	4	13	11.2	0.8
40	1.3	11.8	2.5	15	4	13	16.8	0.81
41	1.3	11.8	2.5	15	4	13	22.4	0.77
42	1.3	11.8	2.5	15	4	13	22.4	0.8
43	1.3	11.8	2.5	15	4	13	8.4	0.85
44	1.3	11.8	2.5	15	4	13	8.4	0.8
45	1.3	11.8	2.5	15	4	13	8.4	0.8
46	1.3	11.8	2.5	15	4	13	16.8	0.77
47	1.3	11.8	2.5	15	4	13	16.8	0.8
48	1.3	11.8	2.5	15	4	13	11.2	0.81
49	1.3	11.8	2.5	15	4	13	8.4	0.82
50	1.3	11.8	2.5	15	4	13	22.4	0.79
51	2.28	0	4.1	0	5.5	5.5	22.4	0.79
52	2.28	0	4.1	0	5.5	5.5	11.2	0.85
53	2.28	0	4.1	0	5.5	5.5	11.2	0.75
54	2.28	0	4.1	0	5.5	5.5	8.4	0.84
55	2.28	0	4.1	0	5.5	5.5	22.4	0.84
56	2.28	0	4.1	0	5.5	5.5	22.4	0.83
57	2.28	0	4.1	0	5.5	5.5	8.4	0.76
58	2.28	0	4.1	0	5.5	5.5	11.2	0.78
59	2.28	0	4.1	0	5.5	5.5	8.4	0.78
60	2.28	0	4.1	0	5.5	5.5	11.2	0.82
61	2.28	0	4.1	0	5.5	5.5	16.8	0.76
62	2.28	0	4.1	0	5.5	5.5	16.8	0.82
63	2.28	0	4.1	0	5.5	5.5	16.8	0.76
64	2.28	0	4.1	0	5.5	5.5	16.8	0.82

65	2.28	0	4.1	0	5.5	5.5	16.8	0.8
66	2.28	0	4.1	0	5.5	5.5	8.4	0.83
67	2.28	0	4.1	0	5.5	5.5	11.2	0.82
68	2.28	0	4.1	0	5.5	5.5	22.4	0.84
69	2.28	0	4.1	0	5.5	5.5	8.4	0.84
70	2.28	0	4.1	0	5.5	5.5	22.4	0.78
71	2.28	0	4.1	0	5.5	5.5	11.2	0.82
72	2.28	0	4.1	0	5.5	5.5	11.2	0.77
73	2.28	0	4.1	0	5.5	5.5	11.2	0.75
74	2.28	0	4.1	0	5.5	5.5	22.4	0.82
75	2.28	0	4.1	0	5.5	5.5	11.2	0.8
76	1.25	0	2.5	0	0	9	11.2	0.8
77	1.25	0	2.5	0	0	9	22.4	0.84
78	1.25	0	2.5	0	0	9	16.8	0.81
79	1.25	0	2.5	0	0	9	8.4	0.81
80	1.25	0	2.5	0	0	9	22.4	0.84
81	1.25	0	2.5	0	0	9	22.4	0.83
82	1.25	0	2.5	0	0	9	22.4	0.81
83	1.25	0	2.5	0	0	9	16.8	0.77
84	1.25	0	2.5	0	0	9	22.4	0.77
85	1.25	0	2.5	0	0	9	16.8	0.84
86	1.25	0	2.5	0	0	9	22.4	0.75
87	1.25	0	2.5	0	0	9	22.4	0.8
88	1.25	0	2.5	0	0	9	11.2	0.77
89	1.25	0	2.5	0	0	9	16.8	0.85
90	1.25	0	2.5	0	0	9	11.2	0.82
91	1.25	0	2.5	0	0	9	16.8	0.8
92	1.25	0	2.5	0	0	9	8.4	0.8
93	1.25	0	2.5	0	0	9	8.4	0.76
94	1.25	0	2.5	0	0	9	8.4	0.8
95	1.25	0	2.5	0	0	9	22.4	0.8
96	1.25	0	2.5	0	0	9	11.2	0.8
97	1.25	0	2.5	0	0	9	16.8	0.8
98	1.25	0	2.5	0	0	9	8.4	0.8
99	1.25	0	2.5	0	0	9	8.4	0.8
100	1.25	0	2.5	0	0	9	11.2	0.8

C VIRTUAL POWER PLANT RELATED RESEARCHES

In this appendix, recent VPP related researches that have been summarized in **Table 2-4**, are presented in detail.

C.1 Virtual Fuel Cell Power Plant

The demonstration project "**V**irtual **F**uel **C**ell **P**ower **P**lant" (VFCPP) was conducted from 2001 to 2005, aiming to develop, to install, to test and to demonstrate a virtual power plant consisting of 31 decentralized stand-alone residential fuel cell cogeneration systems. These low temperature PEM µCHP systems can produce $4.5kW_{el}$ and $9kW_{th}$ simultaneously and were installed in apartments, houses and small businesses across Europe. In this project, both onsite EMS and a **C**entral **C**ontrol **S**ystem (CCS) were developed. The onsite EMS controls the fuel cell, additional peak boiler and a hot water storage system to match the heat production of the system to the heat demand of the premise. The CCS communicates with the onsite EMS and allows the utilities to control the µCHP systems in the case of a power peak demand and defined load profiles.

In the field test, different ways of communication as depicted in **Figure 8-1** were tested. In one way communication, **R**adio **R**ipple **C**ontrol (RRC) systems were installed at five selected fuel cell systems; therefore the RRC's receiver relays either forced a fixed electrical output or one of the five pre-defined load profiles stored within the EMS. Alternatively, the one way signal could be a general switch of the fuel cell system between heat-led or electricity-led mode. In the case of two way communication, the CCS can make more kinds of control decisions for the fuel cell systems based on the real-time data transmitted back to the server.

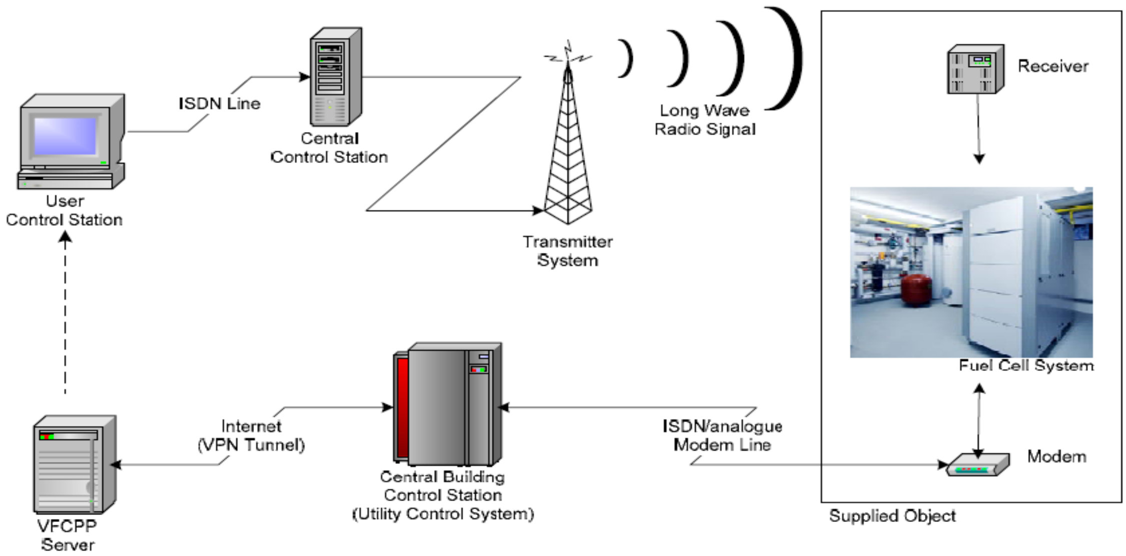

Figure 8-1: Ways of communication in VFCPP field test

Within the accumulated 138,000 running hours, about 50 million measurement data were collected, checked and analyzed, which provided valuable experience for polishing up the current design of LTPEM µCHP systems. Further, the capability of VFCPP to follow pre-defined load profiles without relevant time delay has been successfully demonstrated.

C.2 Virtual Power Plant based on Power Matcher

Power Matcher is a concept developed by the **E**nergy Research **C**entre of the **N**etherlands (ECN) based on multi-agent technology. As shown in **Figure 8-2**, the device agent which represents the DER are clustered by the concentrator agent, who aggregates the market bids into one single bid and communicates this to the auctioneer agent. The responsibility for the auctioneer agent is to perform the price-forming process by searching for the equilibrium price and sends the price back to all the other agents under it. For the objective agent, it is given specific objectives to follow and that decides how the other agents connected to it should behave.

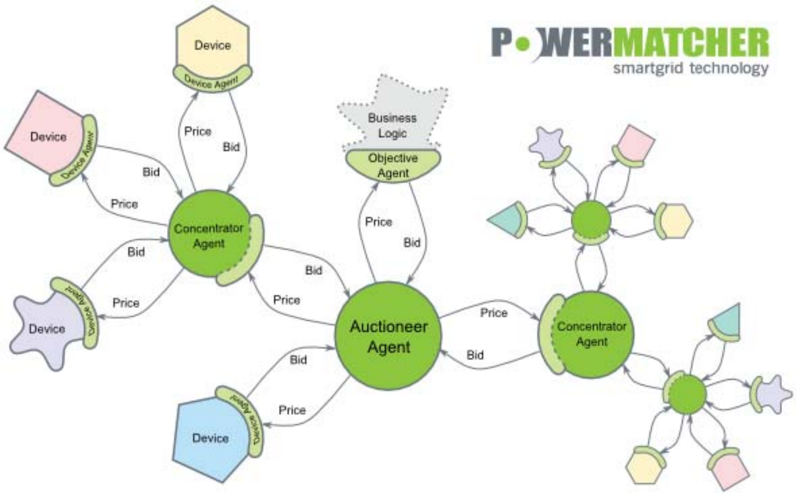

Figure 8-2: Power Matcher Architecture

On the basis of this idea, a VPP field test including 10 Stirling µCHP systems was carried out. The VPP agents run on each µCHP system and communicate with µCHP and thermostats, electric meters through the power line. Wireless communication technology **U**niversal **M**obile **T**elecommunication **S**ystem (UMTS) is implemented between the VPP agents and a Power Matcher server, which contains the market coordination algorithm. During the field test, the Power Matcher server places bids on the market based on a certain demand pattern, resulting in high prices in peak load periods and low prices otherwise. High market prices trigger the µCHP systems to produce electricity, thus reducing the peak load.

Since the test was run in summer, the VPP showed not much capability in peak reduction. This is because some of the end-users only allowed very small bandwidth of their room temperature and no waste heat was allowed to be produced. However, the project team claimed a better result could be expected if the field test was run in winter and also with larger hot water buffers. Further, UMTS proved to be less reliable than expected.

C.3 FENIX Virtual Power Plant

Flexible **E**lectricity **N**etwork to **I**ntegrate the e**X**pected 'Energy Solution' is where FENIX originates from. This four year project FENIX was launched in October 2005, aiming to boost DER by maximizing their contribution to the electric power system, through aggregation into **L**arge **S**cale **V**irtual **P**ower **P**lant (LSVPP) and decentralized management. As shown in **Figure 8-3**, a general FENIX architecture with three core elements: **F**ENIX **B**ox (FB), CVPP and TVPP was developed, wherein:

- The FB interfaces DER control system enabling remote monitoring and control.
- The CVPP is in charge of the scheduling and energy optimization functions of DER group.

- The TVPP, at the **D**istribution **M**anagement **S**ystem (DMS), performs some type of function, for instance: validates the generation schedule, dispatches DER to address voltage and congestion,, etc.

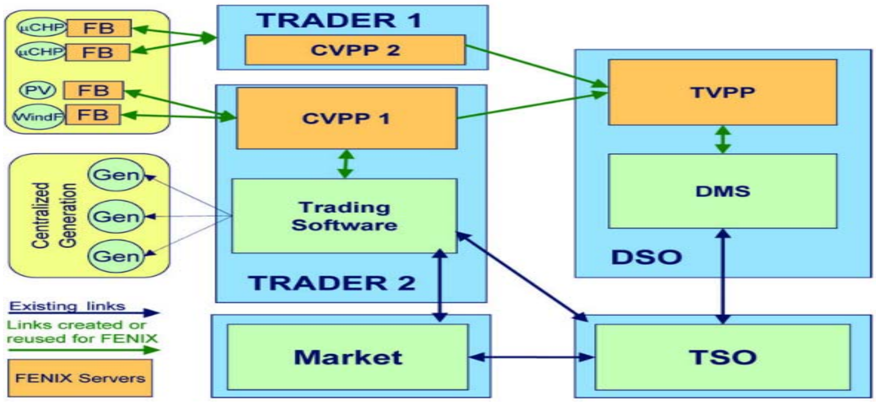

Figure 8-3: The Generic FENIX Architecture

Based on the generic FENIX architecture, there are two demonstrations being hosted by EDF Energy in the UK and Iberdrola in Spain referred to as the Northern scenario and Southern scenarios respectively.

In Northern scenario, as shown in **Figure 8-4**, the aforementioned Power Matcher technology is used to manage the CVPP. The DER portfolio of 3MW of various technologies including a 200kW fuel cell was used in this demonstration. During the operation, the FB provides the Power Matcher device agents with the current state and readings of DER and the agents for particular device determine the individual cost curves and other operational characteristics: generation/load capability, ramp rates, minimum and maximum ‘on’ and ‘off’ times. The Matcher Agent adds all these information together and transfers these to VPP agent, which formulates the bidding curves. The bidding curve is sent to E-terratrade, acting as a market interface, for trading purpose. Once a market transaction is committed, the generation schedule for the CVPP is generated and passed down to all DER devices. In real-time, the DER follow the schedules to produce/consume energy.

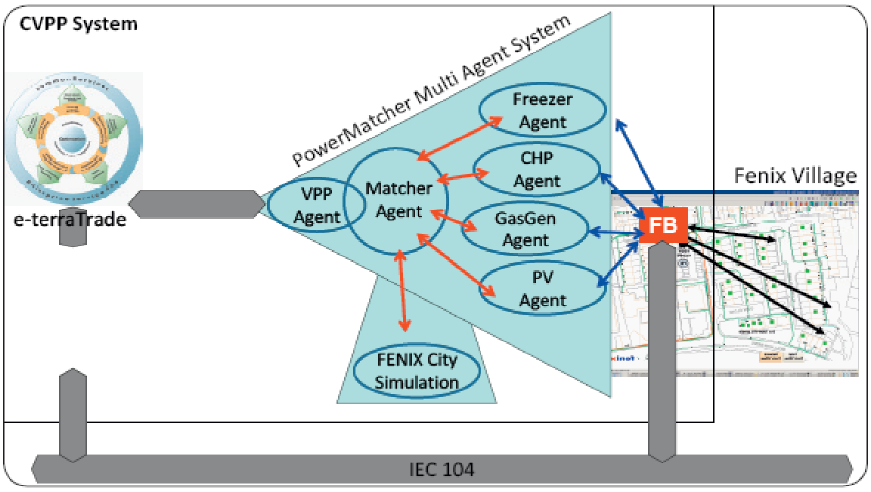

Figure 8-4: Northern Southern Scenario of FENIX (UK)

The Southern scenario of FENIX, as given in **Figure 8-5**, demonstrated both CVPP and TVPP concepts by aggregating a variety of DG technologies in a Distribution system. Most of the DGs are connected to the 30kV grid. During the demonstration, three activities had been successfully demonstrated: participating in the day-ahead market, offering tertiary reserve ancillary service and contributing to voltage regulation in transmission and distribution levels. Like in the Northern scenario, FB provided the interface between DG and local SCADA, which facilitates the integration of DG into the DMS.

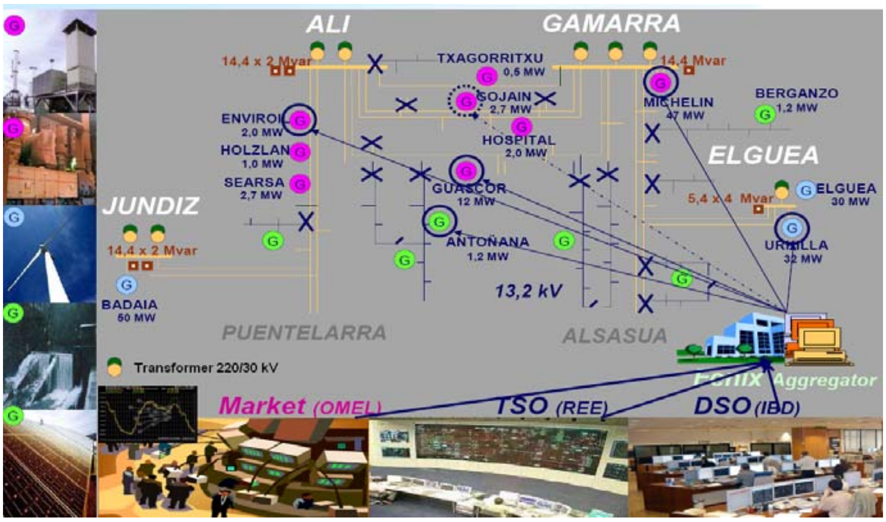

Figure 8-5: Southern Scenario of FENIX (SPAIN)

In both scenarios, GPRS was selected as the communication media between FB and other parties. Further, many valuable conclusions and recommendations regarding the VPP development have been made by the FENIX group, which can be found in [w6].

C.4 EDISON Virtual Power Plant

The Danish EDISON project was launched in 2009, aiming to investigate and address the challenges for EV integration. Finally, the integrated solution will be demonstrated on the Danish island of Bornholm, which corresponds to roughly 1% of Denmark with respect to areas, load and population.

In EDISON project, two different architectural options for VPP were developed, as given in **Figure 8-6**. In the stand-alone architecture, the EDISON VPP (EVPP) has direct access to the electricity market, which forces it to perform internal power balancing. In the Integrated architecture, EVPP provides supportive services to/through already existing market players, like generation companies, in order to achieve effective use of the EV fleet.

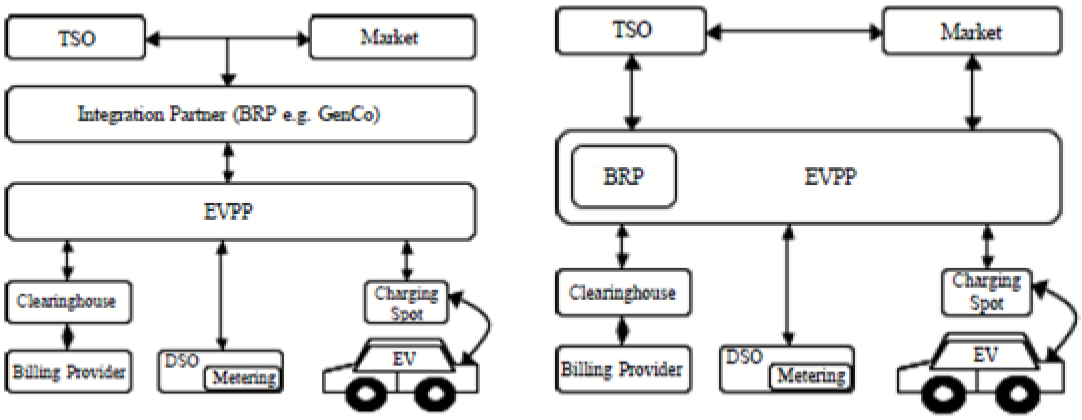

Figure 8-6: EVPP architecture: Integrated EVPP (left) and Standalone EVPP (right)

Currently, the EDISON group considers using centralized control to monitor and optimally dispatch the EV batteries. Although a decentralized control scheme based on real-time price signals was also considered by the consortium, the unlearned features with price signal control such as stability and predictability, etc., have caused a much lower priority to this method.

Besides its special focus given to one of the newest energy resources EV, another highlight of the EVPP is the generic ICT platform. This platform uses **S**ervice **O**riented **Ar**chitecture (SOA) and is developed on the basis of IEC 61850 standard. This ICT platform provides the possibility of supporting a broad range of vendor-independent EVs through a coherent information model, which applies the standardized and service-oriented communication, aiming to develop standard system solutions for EVs which could be applicable globally.

C.5 Professional Virtual Power Plant

The **Pro**fessional **Vi**rtual **P**ower **P**lant pilot project (ProViPP) is a project conducted in October 2008 by RWE (a power plant operator) and Siemens. 9 hydroelectric plants on the Lister and Lenne Rivers in a rural part of Westphalia Germany were interconnected by Siemens' **D**istributed **E**nergy **M**anagement **S**ystem (DEMS) and functioned as a single large plant with an initial output of 8.6MW.

The DEMS is a comprehensive software, executing a series of functions related to market participation for DGs. Based on its forecasted market price for the next day and the information for each power plant, the DEMS makes a quotation for energy trading, which will be checked and approved by the portfolio manager. Once the quotation has been approved, it will be placed on the energy market through an energy trader. The accepted quotation will result in an operating schedule for the individual power plants in the VPP by DEMS. When the time comes, the DEMS monitors the real-time status of the systems, and controls electric power plants as scheduled. Behind this process, Siemens wireless communication devices are used to setup the linkage between each power plant and the control center.

D ATTACHED PAPERS

In this section, selected papers pulished during the PhD research are attached. These papers mainly investigate the issues related to VPP designs and price responsivenss of the μCHP.

A Market-Based Virtual Power Plant

Shi You Student Member IEEE*, Chresten Træholt*, Bjarne Poulsen**

* Technical University of Denmark, Department of Electrical Engineering, Elektrovej 325, 2800 Kgs. Lyngby, (*Denmark*)
** Technical University of Denmark, Department of Informatics and Mathematical Modeling,
Richard Petersens Plads 322, 2800 Kgs. Lyngby, (*Denmark*)

***Abstract*—The fast growing penetration of Distributed Energy Resources (DER) and the continuing trend towards a more liberalized electricity market requires more efficient energy management strategies to handle both emerging technical and economic issues. In this paper, a market-based Virtual Power Plant (MBVPP) model is proposed which provides individual DER units the accesses to current electricity markets. General bidding scenario and price signal scenario as two optional operation scenarios are operated by one MBVPP. In the end, a use case of a MBVPP with micro Combined Heat and Power (μCHP) systems demonstrates the potential benefits and operation scenarios of the MBVPP model.**

***Index Terms*—Distributed Energy Resources, Electricity market, market-based Virtual Power Plant**

I. Introduction

The penetration of Distributed Energy Resources (DER) is growing fast all over the world, which is mainly attributed to the requirement of a sustainable energy system with less environmental pollution, more diversified energy resources and improved energy efficiency [1]. In the meanwhile, the ongoing process of liberalization of the electricity market, i.e. the transition from the former monopolistic to competitive market structures, also attracts more and more attention [2]. In the context of these two tendencies, running a great number of DER units under market conditions is inevitable, which yet poses new challenges that have to be addressed.

- Market participation: Regarded as small, modular power generation, storage technologies and controllable loads [3], DER is generally prohibited from entering the current electricity market [4].
- Intermittent nature: As many DER technologies like photovoltaic systems and wind turbines are weather-dependent, their stochastic output is therefore considered non-dispatchable which not only limits their contribution to grid operation, but also causes economic penalties associated with unexpected unbalances.
- Stand alone: Many DER units are working alone due to their different ownerships. Cooperation and communication often lack between neighboring DER units, thus the capability of DER is confined to satisfy the local needs rather than to complement the entire grid.

One way to address these issues is to aggregate a number of DER units in a so-called Virtual Power Plant (VPP). In this construction, the group of DER units will have the same visibility, controllability and market functionality as the conventional transmission-connected power plants. As aggregation can be guided by functional needs, geographical locations, the nature of generation technologies, points of injection or other kinds of commonalities, designs and implementations of VPP have rarely reached a consensus[5]-[10]. However, VPP can be divided into three basic categories which differ from each other in control architectures and associated information directions.

- Centralized Controlled VPP (CCVPP): requires the VPP has the complete knowledge of involved DER units and defines every operating set point to meet the varying requirements of the local power system [5]-[7].It has a high potential for reaching optimal operation, but is often case specific which results in limited scalability and compatibility.
- Decentralized Controlled VPP (DCVPP): refers to a collection of distributed local controllers which constitute an overall hierarchical architecture [8]. The weakness of CCVPP can be conquered by the modularity and intelligence of local controllers. However, a central controller is still required to sit on top of a DCVPP in order to ensure the system security and an overall economic operation.
- Fully Decentralized Controlled VPP (FDCVPP): is an extension of DCVPP, wherein central controllers are replaced by information exchange agents which only provide valuable services e.g. market price signal, weather forecasting and data logging etc. to FDCVPP participants [9]-[10]. It has a relatively higher scalability and openness than the other architectures as it relies on plug and play ability. In the event of actualizing the internet model of the future power system [11] pictured by the EU research commission, a successful FDCVPP will be taken as the foundation towards operating a fully distributed power system in which every node in the electrical network is awake, responsive, eco-sensitive and price smart.

In this paper, a market-based VPP (MBVPP) model, as one kind of FDCVPP, is proposed. It offers the generic path to small DER units to trade in today's electricity market and takes the advantages of market nature in efficient resources allocation. In section II, a brief review is given to the current electricity market structure, followed by detailed illustrations on design of the MBVPP architecture and associated operation scenarios. In section III, a case study is performed to demonstrate the operation scenarios mentioned in the previous section. Conclusion and directions for future work are offered in Section IV.

II. Design of a MBVPP

The objective of MBVPP is to offer a generic path for

This work was supported by the Danish PSO contract 7572.

all kinds of DER units to get access to today's electricity market; therefore challenges faced by DER can be addressed by the self-regulating capability of the electricity market. In order to achieve this goal, the design of a MBVPP has to be based on the study of today's electricity market principle and to ensure a seamless linkage between the internal MBVPP organized market and the external global electricity market, e.g. Nordpool [12].

A. Time Frame for Today's Electricity market

A general summary of the overall time frame for trading electricity and ancillary services is given in Fig 1. Long term forward contracts take place from months or years before a trade is executed. Day-ahead market provides market participants with the option to play in short term forward market. Sometimes, an intra-day market kicks in and provides continuous power trading up to one hour prior to delivery. Balancing market, also known as regulating market, which extends from real-time to day ahead, is part of the overall energy market that provides balancing power/energy to electric power system operation at a short term notice. Furthermore, market for ancillary services covers a time frame from long term to real time and interacts with all aforementioned energy markets. These services are the processes and actions associated with power system operation, which are provided by market participants and generally managed by the transmission system operators (TSOs). Similar services are procured by distribution system operators (DSOs) for the purpose of maintaining the power system security at the distribution level.

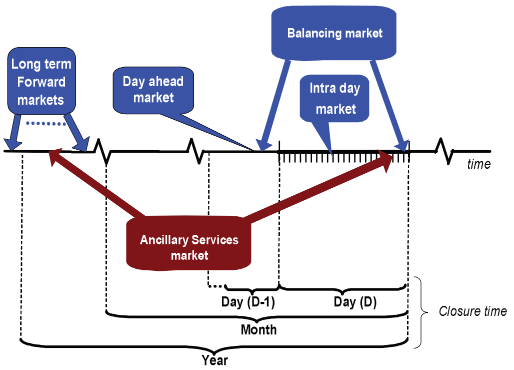

Fig. 1. Time frame for trading electricity & ancillary services

B. Architecture of the MBVPP

As given in Fig 2, a MBVPP provides a platform through which every DER gains a seat in any of the aforementioned electricity markets. In principle, most of the DER units give priority to serving their individual demand; therefore only excessive generation will be sold back to the grid. Electrical power flow goes through the point of common coupling (PCC) from the MBVPP to meet either local demand or demand in other areas across the distribution and transmission system. Generally, a MBVPP can perform activities in at least three distinct fields:

- Electricity Market: A MBVPP is able to trade with any other market player e.g. brokers, traders, DSOs, TSOs and even other MBVPPs in terms of bilateral contracts or power exchange. All the arranged trades have to be checked by TSOs or DSOs to ensure the power system security at different levels.
- Internal Market: A MBVPP acts as a market operator as well as a service operator. It offers different market scenarios like bidding scenario and price signal scenario to meet the different customers' requirements. Bilateral trading can also take place between individual DER units if desired as depicted in Fig 2. As the point of common coupling (PCC) for MBVPP is within the distribution network, DSOs have to be responsible for the security issues within the MBVPP.
- Other Business Fields: If the number of participants increases to a certain level, it may be possible for the MBVPP to intervene in other business fields such as fuel markets and carbon markets or to become a legal entity. Each participant may thus achieve further benefits.

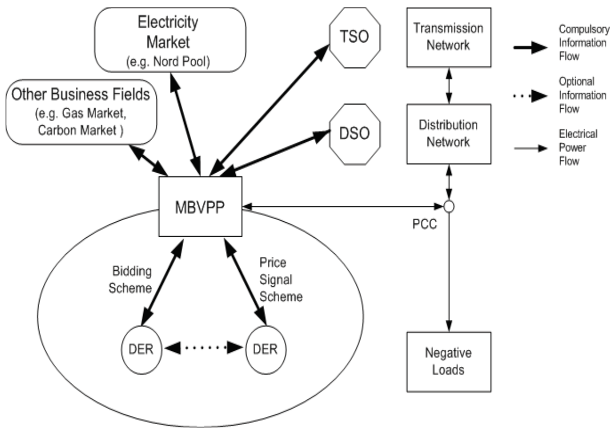

Fig. 2. Architecture of the MBVPP

C. Internal Market Scenarios

In an attempt to make all DER units operate cost-effectively, a MBVPP offers two optional market scenarios in its internal market: general bidding scenario and price signal scenario. Both scenarios are flexible in the time frame of trading, therefore seamless coordination between the internal market and the external market is established. Communication is presumably implemented via the internet under a flawless operation.

1) Scenario 1: General Bidding

DER units who select the general bidding scenario will be paid at the electricity market price if their bids are accepted; therefore the profit is closely related with their own intelligence. An example of applying the internal market scenario to cooperating with the Nord Pool Spot [13], a typical day-ahead market for power exchange, is given in Table I. During this period, the MBVPP operator is only responsible for information exchange with different partners and bid aggregation while each DER has to develop its own optimal operation schedule for the next day based on the MBVPP forecasted information. In terms of fitting into other wholesale market time frames, like hour ahead or 15 minutes ahead, similar routines can be developed.

TABLE I
COOPERATION BETWEEN THE MBVPP'S INTERNAL DAY-AHEAD MARKET AND NORD POOL SPOT

Time	Routine
8:00-10:00	Price forecasts for tomorrow's wholesale market is performed by the MBVPP
10:00-10:30	Bids are submitted by DER owners to the MBVPP's internal day-ahead market
10:30-11:30	MBVPP aggregates the bids
11:30-12:00	MBVPP submits the aggregated bids to Nord Pool Spot
(13:00-14:00)	Nord Pool Spot clears the market and informs the MBVPP
(14:00-19:00)	MBVPP makes a final aggregated production plan
(15:00-19:00)	Final production schedule is submitted to the TSO
(16:00-19:00)	Final production schedule is determined by the TSO and sent back to the MBVPP
19:00-20:00	Final production schedule is sent to DSOs for security check
20:00-21:00	Final production schedule are approved/revised by DSOs and sent back to the MBVPP
21:00-22:00	Each DER unit receives its final production schedule for tomorrow from the MBVPP

Note: Time periods in brackets are realistic with Nord Pool Spot [13]

2) Scenario 2: Price Signal Control

The price signal market scenario allows DER owners to response to a series of price signals published by the MBVPP operator for their generation planning or real time operation. Certain degree of indirect control over the DER units is thus obtained by MBVPP operator through varying price signals; however the intelligence level of MBVPP operator has to be highly raised compared to the one required in the bidding scenario.

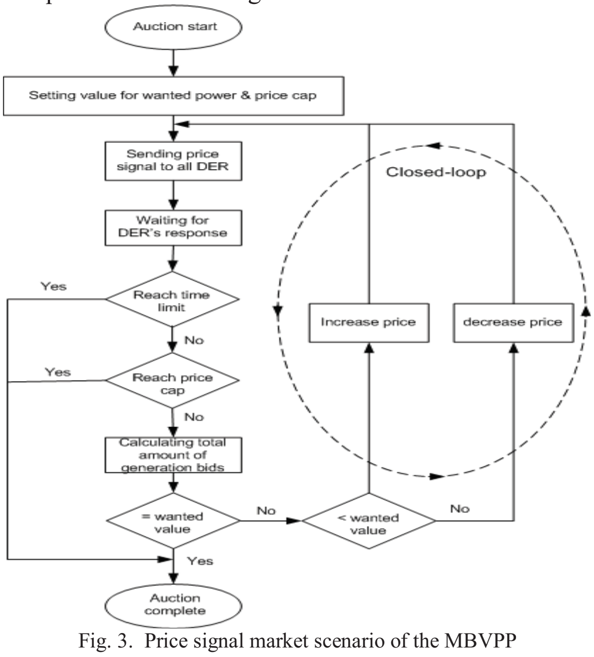

Fig. 3. Price signal market scenario of the MBVPP

As illustrated in Fig. 3, at the beginning of each market round, the MBVPP has to design a package which includes the target value for the volume of wanted power production during a specific time period as well as a price cap. The package can be quoted from either a bilateral contract signed with other market players or part of MBVPP's bidding curve for external market trading which is estimated by MBVPP operator. Generally, the price cap has to be set at a reasonable level in order to guarantee the profit of MBVPP developer. After sending out the first price signal to the DER owners, MBVPP operator has to wait for the responses. If the accumulated power from the feedback is lower than the wanted volume, the buy price will be raised to attract more willingness of DER units to sell their excessive generation. Vice versa, over-positive feedbacks will result in a lower price signal to cut down the overall volume. This closed-loop auction continues till the target value is reached. However, several key factors in this process have to be properly designed to ensure the flawless operation.

a. Number of participants: An auction with few participants can hardly be successful every time. Therefore only a large number of participants with diversified generation portfolios are the basis for implementing the price signal scenario.

b. Time period for each auction round: Basically, the time period for each auction can be very flexible and is only limited by communication barriers. However, if the time period is very short, for instance 1 minute, many DER units may not be able to respond in time. In case of a long period like 30 minutes, the auction may be closed much earlier and leave a time blank. Therefore, investigations over hardware limits and simulations on DER units' behaviors under different auction time periods have to be further exploited to ensure the acute cooperation.

c. Wanted volume: The wanted volume has to be lower than the overall generation capacity of MBVPP. In order to guarantee this, the MBVPP can either estimate its capacity based on the accumulated experience from learning period or make each DER unit report their available capacity before auction starts.

d. Starting price and price change: Certain range has to be reserved between starting price and price cap. Price change Δp between each auction step has to be effective to save communication resources. Therefore, in order to develop a pricing scheme that fulfills these requirements, a comprehensive investigation on DER units' behaviors over different price signals has to be carried out.

Even though the listed factors are well designed, emergency cases, like committed units suddenly turn offline, may still come along. Therefore, having local reserves and close relationships with neighboring energy resources can further enhance the system robustness. In addition, starting another shorter term auction round with emergency price could be another resort.

3) General Bidding vs. Price Signal Control

With both scenarios, MBVPP is able to provide an open platform to all kinds of DER to get access to the energy market without intervening in the decision making process of DER owners. Further, both scenarios can be applied to regulate either forward markets or an almost real time markets.

General bidding scenario as a conventional market scenario which lets market participants bid at the prices with their preferences. This requires high intelligence level for each DER owner, as bidding at a higher price may result in losing the opportunity of selling. Therefore, every owner has to bid at the marginal price of his system in order to pursue extra profit. However, this scenario may frustrate some DER owners if they fail to sell their excessive generation capacity continuously.

As for price signal scenario, DER units can respond to their preferred price levels. Uncertainties associated with the DER behaviors under variable price signals may result in unsuccessful auctions. In this occasion, an intensive pre-study on DER behaviors under variable price signals are necessary to enhance the market robustness under this scenario. Nevertheless, at the early stage of implementing MBVPP, this scenario may be more welcome by the DER owners since the right of decision is to some extent back to them.

From a MBVPP operator's point of view, a general bidding scenario is more reliable than a price signal scenario. A MBVPP running a general bidding scenario can live on the brokerage fees it charged from every participants and leave the risk to the DER owners. On the opposite, a MBVPP running price signal scenario has to bid in the external market based on its estimated capacity and price. As this act is prior to knowing how each DER owner will respond to the MBVPP published price signal, more risk is allocated to the MBVPP operator.

It's possible for a MBVPP to run on either of the two market scenarios independently while another possibility could be running both of them sequentially as they both expose pros and cons. Making general bidding organized internal market compatible with the external day-ahead market or hour-ahead market while making price signal controlled internal market compatible with the real time market may offer a user-friendly market to MBVPP participants, which can further provide experiences for the later internal market designs.

III. Case Study

In this section, general bidding scenario and price signal scenario are applied to a local MBVPP's day-ahead electricity trading and real time trading respectively. Objectives of the case study are to:

- Illustrate the MBVPP concept with a detailed simulated physical system
- Demonstrate the MBVPP internal market scenarios by numeric examples
- Provide the DER units, such as µCHP system, with basic understanding of how to play in the MBVPP's internal market

As given in Fig. 4, the simulated MBVPP system is an expansion of the single µCHP system described in [14], while same symbols are used to describe the system's characteristic. Such system comprises 4 households with different daily load profiles of electricity and thermal consumption. Every household is assumed to be equipped with an identical µCHP system, all of which are connected to a 400V electric feeder. Utility companies are still involved to provide electricity to each household at a fixed price level of 0.115€/kWh. Meanwhile, the natural gas is supplied by fuel suppliers at 0.048 €/kWh which is also assumed to be fixed in the simulation. The MBVPP therefore only buys the excessive electricity from each household after an economic optimization of each µCHP system is carried out by each household. The model for µCHP system with optimized operation under varying electricity buyback price is also quoted from [14] with same assumptions concerning the operation of every single system, while technical parameters for every µCHP system are given in Table II. The simulation is done with GAMS [15].

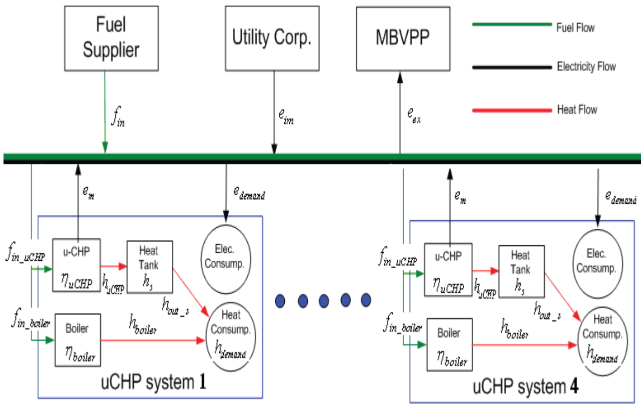

Fig. 4. Physical layout of a MBVPP

TABLE II
List of values for parameters utilized in case study

Technical Assumptions	Elaboration
$f_{\max\_boiler} = 30\ kW$	Auxiliary boiler
$f_{\max\_uCHP} = 24\ kW$	µCHP unit with internal combustion engine driven by natural gas
$h_{s\_\max} = 28\ kWh$	Heat tank is in size of 500 liters with temperature range 20 ºC -70ºC
$\eta_{boiler}(t_i) = 85.5\%$ $\eta_{uCHP}(t_i) = 80\ \%$ $\alpha(t_i) = 2$	Assumed to be fixed over the year (The peak efficiency of modern µCHP unit is around 90%; however 80% is used here since operational conditions with lower efficiency such as start up, shut down and partial load are not taken into account in the simulation)

A. General Bidding Scenario

The general bidding scenario, in this case, is applied to a day-ahead operation scheme. The forecasted load profiles concerning both electrical consumption and thermal consumption of each household for tomorrow are given in Fig. 4, while the spot market price is also predicted by MBVPP given in Fig. 5.

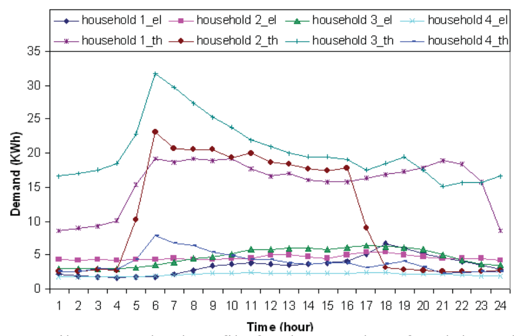

Fig. 5. Daily energy load profile for the next day of each household

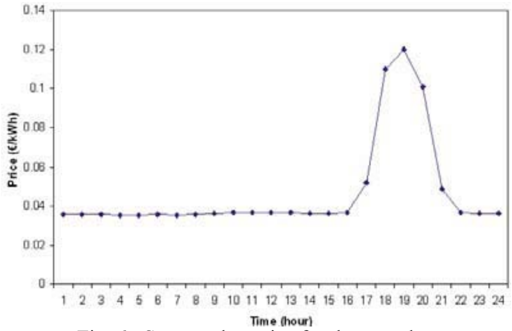

Fig. 6. Spot market price for the next day

Based on the given information, each µCHP system is therefore able to make a cost-minimized generation schedule for tomorrow and bid for their excessive generation at their marginal costs when the trading is conceived profitable. Utilizing the method given in [14], the bidding blocks for each household at every single hour are derived and given in Table III. According to the predicted price curve, at most hours the householders are not willing to inject power back to the grid except for hour 18-20, when there's a price peak coming along. As long as the bids are received by the MBVPP operator, aggregation is carried out to get the overall biding blocks for each hour, as given in Table IV, which is later submitted to the external spot market.

TABLE III
BIDDING BLOCKS OF EACH HOUSEHOLD FOR THE NEXT DAY

Hour	Household 1		Household 2		Household 3		Household 4	
	Amount (kWh)	Price (€/KWH)	Amount (kWh)	Price (€/KWH)	Amount (kWh)	Price (€/KWH)	Amount (kWh)	Price (€/KWH)
1-17	-	-	-	-	-	-	-	-
18	-	-	-	-	0.1895	0.0677	-	-
19	0.48	0.0677	1.4142	0.115	0.2894	0.0677	4.18	0.115
20	1.296	0.0677	-	-	0.6082	0.0677	-	-
21-24	-	-	-	-	-	-	-	-

TABLE IV
AGGREGATED BIDDING BLOCKS OF MBVPP

Hour	MBVPP	
	Amount (kWh)	Price (€/KWH)
1-17	-	-
18	0.1895	0.0677
19	0.7694	0.0677
	5.5942	0.115
20	1.9042	0.0677
21-24	-	-

B. Price Signal Control Scenario

The MBVPP applied with the price signal control scenario is on the assumption that it has to deliver 0.8kWh (±1%) over 5 minutes from 10am. Thus, at 9:55am, the MBVPP operator sets the price cap at 1€/kWh and requests the householders to report their available capacities in the wanted time period. Meanwhile, each µCHP system develops a price function associated with its electrical production. For simplicity, this function is further assumed to be a linear function of available electrical capacity as in (1), and the overall parameter settings are randomly selected in this case as in Table VI, with exception of the values for parameter *a* which are calculated to reflect the cost for generating one unit of electricity under two conditions depending on the accompanied heat production being useful or wasteful [16]. In practice, more concrete price functions regarding different technologies can be developed. Price change Δp between each round of negotiation is also randomly selected by the MBVPP operator.

$$P_{el} = aX + b \tag{1}$$

Where P_{el} is the price, at which the householder wants to sell his excessive electrical capacity (€/kWh); X is the available electrical capacity of µCHP system for the required period (kWh); *a* and b are constants that reflect the market value associated with electrical generation (€) and the householder's add-on value (€/kWh) respectively.

TABLE VI
PARAMETER SETTINGS FOR EACH HOUSEHOLD

	Price Function	Available Electrical Capacity (kWh)
Household 1	$P_{EL1} = 0.18X_1+0.05$	$0 \le X_1 \le 0.5$
Household 2	$P_{EL2} = 0.05X_2+0.09$	$0 \le X_2 \le 0.2$
Household 3	$P_{EL3} = 0.05X_3+0.02$	$0 \le X_3 \le 0.3$
Household 4	$P_{EL4} = 0.18X_4+0.07$	$0 \le X_4 \le 0.4$

The simulated result is illustrated in Fig. 6, wherein it takes 6 rounds to come on to the final agreement. The solid line with cross on it indicates the price change during the negotiation, while the bars represent the replies of each householder following the price change. Final agreement is reached at price 0.0955€/kWh, while the total obtained energy is 0.805kWh.

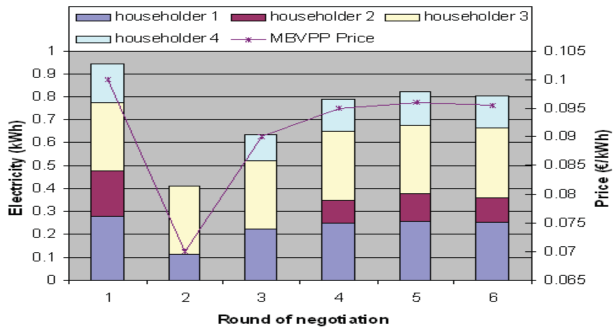

Fig. 7. Process of negotiation

As the two scenarios are applied to different cases, total system cost associated with each scenario is not calculated and compared in this case study. However, when both scenarios are applied to a unique time frame with the same electrical demand in the simulated system, same system costs can be envisioned if Δp is assumed to be infinitely small. In other words, the two scenarios have the same effectiveness in regulating a non-gaming market.

IV. CONCLUSIONS

In this paper, a model for an enabling concept MBVPP is proposed to integrate DER to the current electricity market as well as the electrical grid via its internal market. Economic operation of and extra contributions to the electrical grid made by every DER unit are therefore achieved, thanks to the nature of the market. In addition to providing seamless connections between the internal market and the external market, a general bidding scenario and a price signal control scenario, being two flexible alternatives, are explained, compared and utilized to regulate the internal market of MBVPP. A case study of a MBVPP comprising four µCHP systems is carried out to demonstrate both market scenarios.

The work presented in this paper is part of the work in developing a generic VPP. Further exploration of related topics, such as developing an efficient pricing scheme used in the price control scenario, investigating diversified DER generation portfolios, testing the internal market efficiency and developing emergency operation schemes, is necessary. Finally, analysis is recommended to be done to reveal the possible impacts to current electricity market when a large number of MBVPPs are introduced.

REFERENCES

[1] ENIRDGnet: *Concepts and opportunities of Distributed Gneration: The Driving European Forces and Trend.,* ENIRDGnet Project deliverable D3, 2003

[2] Junichi Ogasawara: *Current status and Evaluation of Electricity market liberalization in Japan, USA and Europe.* IEE 391st regular research session, May 2005.

[3] Friedman, N. R.: *Distributed Energy Resources Interconnection Systems: Technology Review and Research Needs*, National Renewable Energy Laboratory Report No. NREL/SR-560-32459, September 2002.

[4] Ropenus, S.; Skytte, K.: *Regulatory Review and Barriers for the Electricity Supply System for Distributed Generation in the EU-15*, International Journal of Distributed Energy Resources, Vol. 3, 2007, pp. 243-257,

[5] *European Virtual Fuel Cell Power Plant Management Summary Report,* 2005

[6] Caldon, R.; Rossi A.; Turri, R.: *Optimal Control of a Distribution System with a Virtual Power Plant.* Bulk Bulk Power System Dynamics and Control-VI, Italy, Aug. 2004

[7] Bignucolo, F.; Caldon, R.; Prandoni, V.: *The Voltage Control on MV Distribution Networks with Aggregated DG Units (VPP),* Proceedings of the 41st International Volume 1, Sep 2006, pp. 187-192

[8] Wu, F.F.; Moslehi, K.; Bose, A.: *Power System Control Centers: Past, Present, and Future*, Proceeding of IEE, Vol.93, November 2005, pp.1890-1907

[9] Kamphuis, I.; Kok, J.; Wamer, C.; Hommelberg, M.: *Massive Coordination of Residential Embedded Electricity Generation and Demand Response Using the PowerMatcher Approach*, in the 4th International Conference on Energy EFFICIENCY IN Domestic Appliances and Lighting- EEDAL06, 2007

[10] Rasmus Skovmark, Johan Holkmann Jacobsen: *Analysis, Design and Development of a Generic Framework for Power Tradin,* M.Sc thesis, available from Technical University of Denmark, 2007

[11] European Commission: *New ERA for electricity in Europe: Key Issues, Challenges and Proposed Solutions,* EUR 20902, 2003, ISBN 92-894-6262-0

[12] Nord POOL*: http://www.nordpool.com/en/*

[13] Nordpool Spot: *http://www.nordpoolspot.com/*

[14] Shi You, Chresten Træholt, Bjarne Poulsen: *A Study on Electricity Export Capability of the µCHP System with Spot Price,* accepted to be published in the Proceedings and presented at the 2009 PES General Meeting, July, 2008 Canada

[15] GAMS: *http://www.gams.com/*

[16] Jörgen Sjödin, Dag Henning: *Calculating the marginal costs of a district-heating utility,* Applied Energy 78, 2004, pp.1-18

A Study on Electricity Export Capability of the µCHP System with Spot Price

Shi You, Chresten Træholt, Bjarne Poulsen

***Abstract*-- When a number of µCHP systems are aggregated as a Virtual Power Plant (VPP), they will be able to participate in the electricity wholesale market with no discrimination compared to conventional large power plants. Hence, this paper investigates the electricity export capability of the µCHP system when the electricity buyback price is given at a value equalizing the dynamic spot price. A µCHP system is modeled with optimized generation, and the marginal price of electricity export for such system is explained. A sensitivity analysis of several key factors, e.g. fuel price, heat to power ratio of the µCHP unit, which influence the export capability of µCHP system, is firstly carried out in the intraday case study, followed by the annual case study which explores the annual system performance. The results show that the electricity export capability of a µCHP system is closely related to its technical parameters, the associated energy price during the trade, as well as the demand profile. Furthermore, the µCHP system running under fluctuating spot price is likely to gain more profit than that running under a fixed electricity export price.**

***Index Terms*-- marginal price, sensitivity analysis, spot price, Virtual Power Plant, µCHP system**

I. Introduction

Combined Heat and Power (CHP) plant, representing the distributed energy resources (DER), provides significant reductions in carbon emissions and costs by generating both heat and electricity locally with efficient use of fuel and by offsetting the use of centrally-generated electricity from the grid. In recent years, much interest has been put into producing and deploying µCHP systems for use in small commercial and residential environments as the trend towards a decentralized electricity system with diversified electricity production is becoming more and more apparent [1]-[3]. For small commercial applications, the µCHP devices with tens of kW_{el}, which are mainly based on Internal Combustion Engine (ICE) technology, have been commercially available for many years. For residential applications, most available µCHP units with several kW_{el} are based on Stirling Engine technology. Fuel cell-based µCHP systems are currently thought to be a few years away from large scale deployment [4], they are believed to introduce higher degree of carbon savings due to their high electricity efficiency.

However, similar to other DER units, the µCHP units are often operated independently and lack of efficient participation in the electricity market. The former weakness limits the add-on values of µCHP systems, e.g. providing ancillary services, which could benefit both the power system and the µCHP owners; while the latter weakness results in non-optimized operations of µCHP systems when their operations don't follow the market change which indicates an immediate resource allocation of the energy society.

One of the solutions to the mentioned issues connecting small-scaled DER units like µCHP to the grid is to use a concept so-called Virtual Power Plant (VPP), which could be simply considered as an aggregation approach. The European project CRISP provided a short definition in [5]: A Virtual Power Plant is "an aggregation of DER units dispersed among the network, but controllable as a whole generating system". Other definitions have been provided by the European project FENIX [6] and the European Virtual Fuel Cell Power Plant [7] as well as in many academic papers[8]-[10]. Although the definition of VPP varies as the method of aggregation changes from one to another, it can be basically categorized in two groups: indirect controlled VPP and direct controlled VPP.

Indirect Controlled VPP: uses incentives like variable pricing concerning both generation and consumption to encourage the DER units to decide locally in order to maximize their profit. A VPP organized electricity market could be made available to take care of the energy balance and to create increasing profit margins for DER units as given in Fig. 1. The aggregator, in this case, can not define the behaviors of the DER units by setting target values but can control the DER units by varying the incentives of energy purchasing or consuming on a statistical basis.

Direct Controlled VPP: performs a direct control over its joined DER units based on the acquired information, such as market price, contract types, available transmission capability, from the wholesale electricity market and the grid. The whole group of DER units is thus operated optimally to some extent, depending on the intelligence level of the VPP aggregator.

This work was part of project 'Generic Virtual Power Plant for Optimized micro CHP Operation and Integration', and was supported in part by the Technical University of Denmark (DTU) and industrial partners: Danfoss, EC Power and Syd Energi..

Shi You is with the Centre for Electric Technology, Department of Electrical Engineering, Technical University of Denmark, Kgs. Lyngby DK2800, Denmark (e-mail: sy@elektro.dtu.dk).

Chresten Træholt is with the Centre for Electric Technology, Department of Electrical Engineering, Technical University of Denmark, Kgs. Lyngby DK2800, Denmark (e-mail: ctr@elektro.dtu.dk).

Bjarne Poulsen is with the Centre for Electric Technology, Department of Informatics and Mathematical Modeling, Technical University of Denmark, Kgs. Lyngby DK2800, Denmark (e-mail: bjp@imm.dtu.dk).

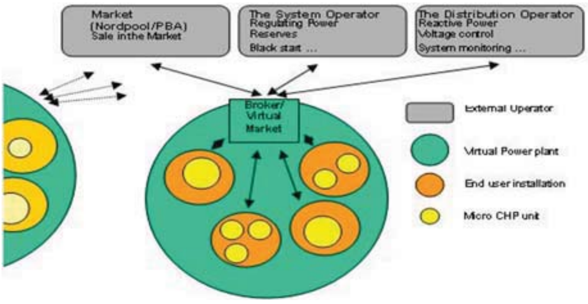

Fig. 1. A structure for market-based Virtual Power Plant

Disregarding the uncertainness introduced by varying aggregation approaches, small DER units like the µCHP are yet believed to have more efficient market participation through VPP in the future. Based on the varying market price, the price-responsiveness of these units would benefit both themselves and the grid operator. For instance, high electricity market prices that imply insufficient energy supplies will be attractive for µCHP units to generate more electricity and sell it back to the grid which in turn alleviates a critical situation.

The paper investigates the electricity export capability of the µCHP system under the VPP scheme, meaning the electricity buyback price is given at a value equalizing the dynamic market price. A µCHP system with optimized generation was modeled in Section II, while the marginal price of electricity export for such system is also explained in the same section. Section III shows the result of a case study, wherein the µCHP system model applied with spot market price is utilized to meet the demand of a multi-family house. The intraday analysis including sensitivity studies on specific factors and the annual analysis on system electrical performance are both done in this part, respectively. Section IV concludes the paper.

II. Model of a µCHP System with Cost Minimization

In Fig. 2 a model of the relevant µCHP system, modified from [11], is presented. A multi-family house installed with a µCHP unit and the auxiliary units, e.g. boiler and heat tank, interacts with other energy entities. Primary fuels like natural gas or oils are supplied by the fuel supplier and electricity is fed in by the utility company. The excessive electricity produced by the system is bought by a local VPP at the spot market price. The symbols of all the energy flows depicted in Fig. 2 and the accompanying prices are shown in Table I , noticing that they are all none-negative.

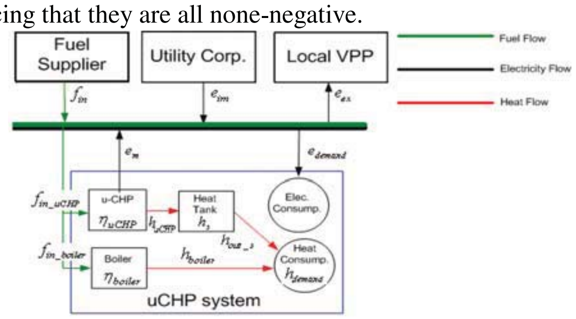

Fig. 2. Model of a µCHP system for a multi-family house

TABLE I
LIST OF SYMBOLS IN µCHP SYSTEM MODEL

$t_i, i = 1 \cdots n$	A specific time slot and the total number of time intervals in one optimization period
$f_{in}(t_i), P_{ng}(t_i)$	Total primary fuel input (kWh) for the system and its price (€ /kWh) at t_i
$f_{\max\_uCHP}, f_{\max\_boiler}$	Maximum fuel input (kWh) for µCHP and boiler respectively
$f_{in\_boiler}(t_i), h_{boiler}(t_i)$	Fuel input (kWh) for boiler and its thermal generation (kWh) at t_i
$f_{in\_uCHP}(t_i), \alpha(t_i)$	Fuel input (kWh) for µCHP unit and the heat to power ratio of the unit at t_i
$\eta_{boiler}(t_i), \eta_{uCHP}(t_i)$	Total energy generation efficiency of boiler and µCHP unit in % at t_i
$h_s(t_i), h_{out\_s}(t_i), h_{s\_\max}$	The heat stored (kWh) in heat tank at the end of t_i, heat output (kWh) of heat tank at t_i and the maximum storage capability of heat tank (kWh)
$e_{uCHP}(t_i), h_{uCHP}(t_i)$	Electrical production (kWh) and thermal production (kWh) of µCHP unit at t_i
$e_{ex}(t_i), P_{ex}(t_i)$	Exported electricity (kWh) and its price (€ /kWh) at t_i
$e_{im}(t_i), P_{im}(t_i)$	Imported electricity (kWh) and its price (€ /kWh) at t_i
$h_{demand}(t_i), e_{demand}(t_i)$	Electrical demand (kWh) and thermal demand (kWh) at t_i
$C_{marginal}(t_i)$	The marginal price (kWh) for electricity export at t_i
$Cost(t_i)$	System cost (€) for t_i

In this process, a group of equations indicating physical energy balances are given as follows:

Production Balance:

$$f_{in\_boiler}(t_i) \cdot \eta_{boiler}(t_i) = h_{boiler}(t_i) \tag{1}$$

$$f_{in\_uCHP}(t_i) \cdot \eta_{uCHP}(t_i) \cdot \frac{\alpha(t_i)}{1+\alpha(t_i)} = h_{uCHP}(t_i) \tag{2}$$

$$f_{in\_uCHP}(t_i) \cdot \eta_{uCHP}(t_i) \cdot \frac{1}{1+\alpha(t_i)} = e_{uCHP}(t_i) \tag{3}$$

Fuel Balance:

$$f_{in\_boiler}(t_i) + f_{in\_uCHP}(t_i) = f_{in}(t_i) \tag{4}$$

Electrical Balance:

$$e_{uCHP}(t_i) + e_{im}(t_i) - e_{ex}(t_i) = e_{demand}(t_i) \tag{5}$$

Thermal Balance:

$$h_{boiler}(t_i) + h_{out\_s}(t_i) = h_{demand}(t_i) \tag{6}$$

Thermal Storage Balance:

$$h_{uCHP}(t_i) + h_s(t_{i-1}) = h_{out\_s}(t_i) + h_s(t_i) \tag{7}$$

Subject to capacity limit of every device:

Capacity limit of boiler:

$$f_{in\_boiler}(t_i) \le f_{\max\_boiler} \tag{8}$$

Capacity limit of µCHP:

$$f_{in\_uCHP}(t_i) \le f_{\max\_uCHP} \tag{9}$$

Storage limit of heat tank:

$$h_s(t_i) \le h_{s\_\max} \tag{10}$$

The object of such system, as in (11), is to minimize the total cost for one optimization period which includes n time intervals.

$$\sum_{i=1}^{n} \mathrm{cost}(t_i) = \sum_{i=1}^{n} \left[f_{in}(t_i) \cdot p_{ng}(t_i) + e_{im}(t_i) \cdot p_{im}(t_i) - e_{ex}(t_i) \cdot p_{ex}(t_i) \right] \tag{11}$$

By knowing the information regarding both energy prices and demand profiles in advance, the µCHP system is capable of generating a cost-minimized production schedule. The schedule defines the setting point of each unit within its generation margin at every time interval. The heat demand is met by either μCHP unit or the auxiliary boiler or both, depending on an economic evaluation of the system cost. Heat tank as the thermal storage unit, provides more flexibility to μCHP system during electricity export. In other words, the μCHP system could generate more electricity for export purpose while storing the excessive heat in heat tank in the case of low heat demand but with high electricity export price. In real time, the system follows the schedule and meets its local demand with the least system cost. During this process, several assumptions are made and listed below:

- Precise prediction on energy prices and local demand, this could be possible as long as the VPP has a reliable forecasting system and the optimization period is very close to real time, like 5 minutes ahead;
- Intelligent modules with both computational capabilities and controllability are installed in the system;
- The whole system is lossless;
- Heat dump is not allowed;
- Start up cost and shut down cost are ignored;

The marginal price for electricity export of such system is a time dependent variable. It indicates the price level at which the μCHP system is willing to produce one more unit of electricity for export. It can be derived by comparing the optimized schedules under zero buyback price and marginal price.

When $P_{ex}(t_i) = 0, \forall i = 1 \cdots n$, the total system cost can be calculated as $Cost(t^-)$, indicating the total system cost for previous schedule in one optimization period.

When $P_{ex}(t_a) = C_{\text{margin}}(t_a)$, and $P_{ex}(t_i) = 0, \forall i = 1 \cdots a-1, a+1 \cdots n$, the total system cost can be calculated again as $Cost(t^+)$, indicating the total system cost for the new schedule in the same optimization period.

Once $Cost\ (t^-) = Cost\ (t^+)$, the marginal price for the specific time interval t_a can be derived. By repeating this, the marginal prices for all intervals in one optimization period can be found.

For the buyback price at a specific time interval, it doesn't incur any electricity export until it exceeds the corresponding marginal price and further results in a less system cost for the whole optimization period.

In the situation that the optimization period only includes one time interval t_i, the marginal price equation can be simply derived as follow:

$$\frac{h_{boiler}(t^+)}{\eta_{boiler}(t^+)} \cdot P_{fuel}(t) + \frac{e_{uCHP}(t^+) \cdot (1+\alpha)}{\eta_{uCHP}(t^+)} \cdot P_{fuel}(t) - \{e_{uCHP}(t^+) - e_{uCHP}(t^-) - e_{im}(t^-)\} \cdot C_{\text{marginal}}(t)$$
$$= \frac{h_{boiler}(t^-)}{\eta_{boiler}(t^-)} \cdot P_{fuel}(t) + e_{im}(t^-) \cdot P_{im}(t) + \frac{e_{uCHP}(t^-) \cdot (1+\alpha)}{\eta_{uCHP}(t^-)} \cdot P_{fuel}(t) \qquad (12)$$

The right side of (12) depicts the system cost when there is no electricity export since the buyback price is zero. It comprises the boiler cost, the cost for imported electricity as well as the cost for μCHP generation. The left side of (12) describes the updated system cost when electricity export occurs at the marginal price of μCHP system. From the equation, it's easy to find that the marginal price for electricity export is closely related to the technical parameters of each device and the energy prices involved in the trading process.

The marginal price derived in (12) is different from the value derived when the optimization period consists of many continuous time intervals. It is because the latter situation couples the marginal price for one time interval with the other time intervals. This theoretically leads to a more cost-effective schedule than the one optimizing a single time interval, since the storage capacity at this time interval can be saved for latter use when a higher buyback price is foreseen in the coming time interval.

III. Case Study

In the case study, the μCHP system is applied to a multi-family house. It aims at explore the export capability of the μCHP system based on the marginal price method given in section II. The annual demand profile for the house is on hourly basis and its average monthly profile is given in Fig. 3. Both intraday and annual analyses concerning the system performance are carried out in this section, wherein an annual hourly spot price from NordPool [12] is assumed to be electricity buyback price. Each optimization period is defined as a day and the time interval is thus considered as an hour. In the intraday analysis, sensitivity study concerning the marginal price of electricity export for the modeled μCHP system is done with three factors, P_{ng} , η_{uCHP} and α in both summer day and winter day. Following that, annual economic performance and export performance of such system are evaluated and further compared with the same system running under a fixed buyback price equalizing the average spot price. Values for the parameters used in the case study are given in Table II. Assumption made in section II also applies to the case studies, furthermore several variables are assumed to be fixed as shown in Table II. As a linear optimization problem, GAMS [13] is employed to simulate the process and find out the optimal solution.

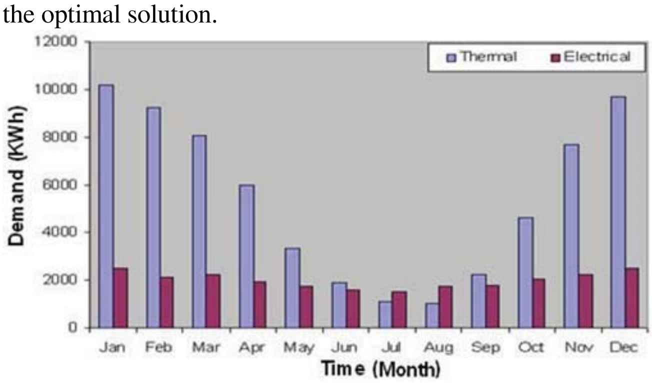

Fig. 3. Demand Profile for Multi-family House

A. Intraday Study

The intraday study includes studies on both winter day and summer day. Sensitivity analysis, including 4 scenarios:

system with original settings, system with -10% gas price, system µCHP efficiency equals 88%, system with µCHP unit's heat to power ratio equals one, are carried in winter and summer, respectively. In each scenario, values for all the parameters are cited from TABLE II except for the indicated parameter.

TABLE II
LIST OF VALUES FOR PARAMETERS UTILIZED IN CASE STUDY

$f_{\max\_boiler} = 30\ kW$	Auxiliary boiler
$f_{\max\_uCHP} = 24\ kW$	µCHP unit with internal combustion engine driven by natural gas
$h_{s\_\max} = 28\ kWh$	Heat tank is in size of 500 liters with temperature range 20 °C -70°C
$\eta_{boiler}(t_i) = 85.5\%$	Assumed to be fixed over the year (The peak efficiency of modern µCHP unit is around 90%; however 80% is used here since operational conditions with lower efficiency such start up, shut down and partial load are not taken into account in the simulation)
$\eta_{uCHP}(t_i) = 80\ \%$	
$\alpha(t_i) = 2$	
$P_{ex}(t_i)$	Hourly price from spot market of NordPool
$P_{im}(t_i) = 0.115$ € /kWh	Assumed to be constant tariffs over the year
$P_{ng}(t_i) = 0.048$ € /kWh	
$h_{demand}(t_i), e_{demand}(t_i)$	Hourly basis

Case 1: Winter Day

As given in Fig. 4, the hourly based demand profile in the studied winter day has a very high heat to power ratio. When the parameter settings is kept the same as given in TABLE II, the marginal price for such system is around 0.0677€ /kWh in most hours except for hour 18, in which the marginal price is an infinite value. This is because the µCHP system has exerted all its power to meet the peak electrical demand at hour 18, export is thus impossible. Following the peak of spot price, export starts at hour 19 and hour 20, as shown in Fig. 5.

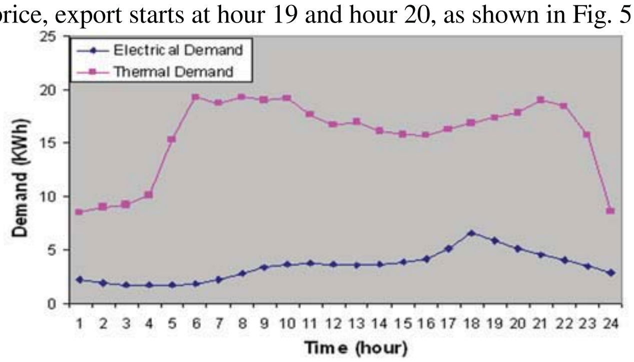

Fig. 4. Demand Profile for Multi-family House in a Winter Day

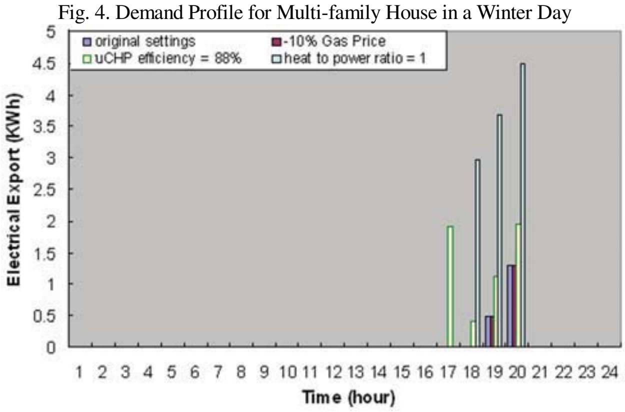

Fig. 5. Electrical Export for Different Scenarios in a Winter Day

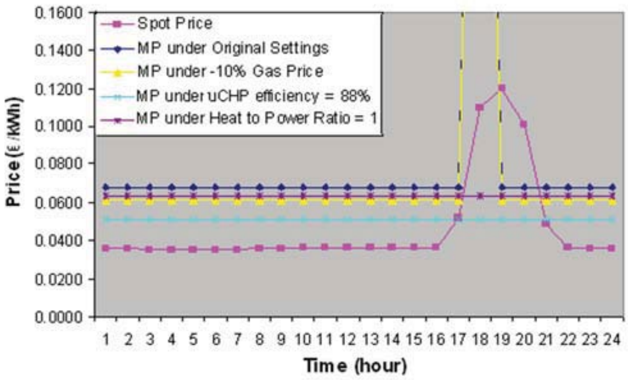

Fig. 6. Marginal Price for Different Scenarios VS Spot Price in a Winter Day

As presented in Fig. 5 and Fig. 6, changes to the parameter settings can cause a deviation of marginal price from the values derived under original system settings. The scenario with µCHP efficiency equals 88% results in the lowest marginal price at 0.0514€/kWh, and this further leads to continuous electricity export from hour 17 to hour 20. The scenario with heat to power ratio of µCHP unit equals 1 has a higher marginal price than the one with lower gas price; however as the electrical efficiency is accordingly increased by 10%, the µCHP unit has more excessive electricity than that of the other scenarios.

Case 2: Summer Day

As given in Fig. 7, in contrast to the hourly based demand profile in a winter day, heat to power ratio of the demand in a summer day is less than 1 in most of the time. This results in a lot extra heat when the µCHP system generates electricity. In turn, the extra heat limits the export capability of such system and incurs a pretty high marginal price for electricity export. The marginal price given in Fig. 8, is equal to the electricity import price in all previous scenarios explored in a winter day. This is because varying only one parameter in a reasonable range as before is not enough to incur an efficient electricity production than buying it from the grid. Therefore, another scenario with both increased µCHP efficiency and lowered heat to power ratio of the µCHP unit is conducted. A lower marginal price at 0.1091€/kWh can be derived, as given in Fig 8. However, this is still much higher than the spot price. No electricity is injected back to the grid in this summer day.

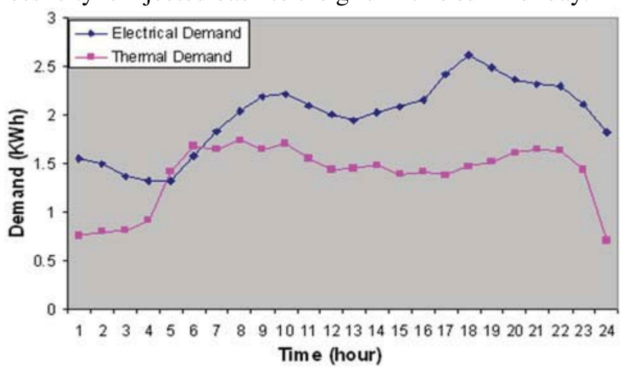

Fig. 7. Demand Profile for Multi-family House in a Summer Day

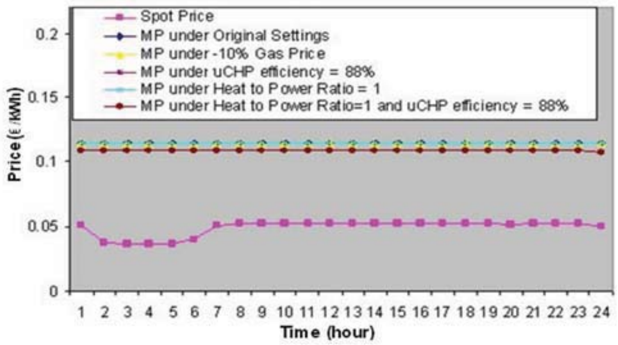

Fig. 8. Marginal Price for Different Scenarios VS Spot Price in a Summer Day

B. Annual Study

Utilizing the values for parameter given in TABLE II and the annual hourly spot price given in Fig. 9, the optimization process in each day is run through the whole year. Simulated result is given Fig. 10. It shows that such μCHP system can export little electricity in winter and spring. No electricity is exported in summer and fall, since the low heat demand results in relative high marginal prices.

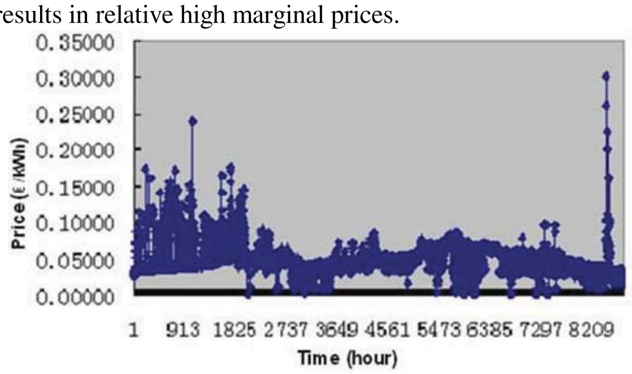

Fig. 9. Hourly Price of NordPool Spot Market in 2006

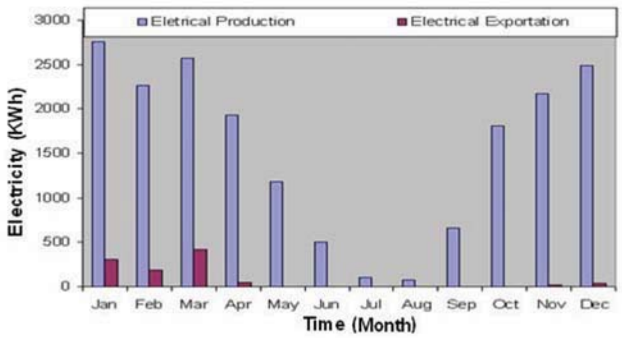

Fig. 10. Annual Electrical Performance of μCHP System under Spot Price

Similar study on the annual electrical performance of μCHP system is done with fixed buyback price. The price is considered to be the average value of spot price, equalizing 0.048€/kWh. As depicted in Fig. 11, μCHP system under such pricing scheme export none electricity to the grid. Although less electricity is produced by μCHP system in such scheme, the annual cost is a little higher than that under the spot price scheme.

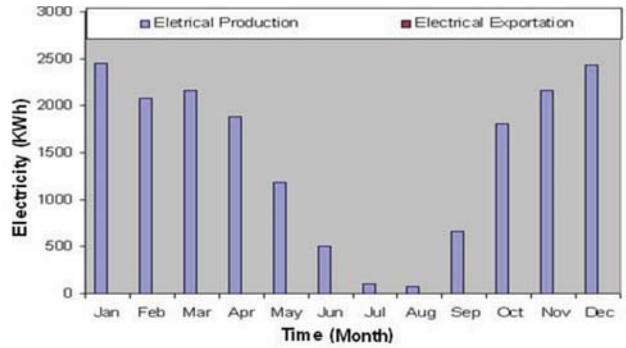

Fig. 11. Annual Electrical Performance of μCHP System under Fixed Price

Table III summarizes the μCHP system performance under different pricing schemes of electricity export. The μCHP system under spot price is found to be with less system cost and more electricity production. In other words, variable export price for electricity may save little for the μCHP owners, but it does incur more exported electricity from such small units. This would ultimately make great contributions to alleviate the inadequacy of electricity supply at critical moments if more μCHP units are deployed efficiently in the power system.

TABLE III
COMPARISON OF SYSTEM PERFORMANCE UNDER DIFFERENT PRICING SCHEMES

Pricing Scheme	Total Cost (€)	Generated Electricity (kWh)	Exported Electricity (kWh)
Spot Price	4223.6	18521	1037
Fixed Price	4243.6	17484	0

IV. CONCLUSIONS

This paper investigates the electricity export capability of a μCHP system getting dynamic export price through a Virtual Power Plant. This study provides the foundation for VPP developers and system operators to develop rational pricing schemes, which shall maximize the utilization of DER units in a more efficient way.

Based on the proposed cost-minimized μCHP model, marginal price for electricity export of such system is explained. Case studies demonstrate that the marginal price for a μCHP system is higher than the spot price in most time of the year. However, as the spot price fluctuates dramatically in spring and winter, some electricity can be sold back to the grid in case of a high spot price. In the context of very low heat demand, especially in summer, high marginal price is found when heat dumping is not allowed. The change of marginal price for μCHP systems indicates that such systems would be utilized more efficiently if they were installed at places with high thermal demand during the year.

Variable price for electricity export can exert more electricity from μCHP systems than fixed export price. However, in order to completely use the electricity export capability of μCHP systems especially in summer days, VPP developers may have to develop more effective dynamic pricing schemes rather than using spot price.

V. References

[1] A.D. Peacock, M. Newborough, "Impact of micro-combined heat-and-power systems on energy flows in the UK electricity supply industry", *Energy* 31, 2006, pp. 1804-1848

[2] Newborough, M, "Assessing the benefits of implementing micro-CHP systems in the *UK", Proceedings of the I Mech E Part A Journal of Power and Energy,* 2004, 218(4), pp. 203-218

[3] Harrison, J.D., "Micro combined heat and power: potential impact on the electricity supply industry", *Proceedings of 16th International Conference on Electricity Distribution*, 2001

[4] ACEEE "Commercial Micro-CHP Using Fuel Cells and Micro turbines" Emerging Technologies & Practices: 2004. [Online]. Available: http://www.aceee.org/pubs/a042_p2ab.pdf

[5] C. Andrieu, M.Fontela, B. Enacheanu, H. Pham, B. Raison, "Distributed Network Architectures", European project CRISP, Deliverable D 1.7, 30 August 2005. [Online]. Available: http://crisp.ecn.nl/deliverables/D1.7.pdf

[6] D. Pudjianto, C. Ramsay, G. Strbac, "Virtual power plant and system integration of distributed energy resources", *IET Renewable Power Generation* 1, 2007, pp. 10-16.

[7] A. Dauensteiner, "European Virtual Fuel Cell Power Plant – Management summary report", February, 2007. [Online]. Available: http://ec.europa.eu/energy/res/sectors/doc/polygeneration/euvpp.pdf

[8] J.K. Kok, C.j. Warmer, I.G. Kamphuis, "PowerMatcher: Multiagent Control in the Electricity Infrastructure", AAMAS-05, Utrecht, 25-29 July 2005.

[9] D. Coll-Mayor, R. Picos, E. Garcia-Moreno, "State of the art of the virtual utility: the smart distributed generation network", *International Journal of Energy Research*, 28, 2004

[10] Schulz, C., Roder, G., "Virtual Power Plants with combined heat and power micro-units", *Future Power Systems*, 2005, Int. Conf. on 16-18 Nov. 2005

[11] Houwing, M., & Negenborn, R.R, "Model predictive least cost control of residential energy resources when applying µCHP", *Proceedings of the IEEE Power Tech 2007 conference*

[12] Power Exchange NordPool Spot: http://www.nordpoolspot.com/

[13] General Algebraic Modeling System: http://www.gams.com/

VI. Biographies

Shi You received the B.Sc. degree in Electrical Engineering from Harbin Institute of Technology, China, and the M.Sc. degree in Electrical Engineering from Chalmers Institute of Technology, Sweden in 2004 and 2006 respectively. He is currently pursuing the PhD degree in department of Electrical Engineering at the Technical University of Denmark. His main fields of interest are renewable energy and electricity market.

Chresten Træholt is an Associate Professor at Centre for Electric Technology, Technical University of Denmark. He received a PhD. in Material Science from the Technical University of Denmark in 1995. His main fields of interests are distributed generation, superconductor technology and superconducting cables.

Bjarne Poulsen is an Associate Professor of Department of Informatics and Mathematical Modeling at The Technical University of Denmark. He earned a PhD. in Electrical and Computer Engineering from The Technical University of Denmark in 1996, a master from Aalborg University in 1990.

GENERIC VIRTUAL POWER PLANTS: MANAGEMENT OF DISTRIBUTED ENERGY RESOURCES UNDER LIBERALIZED ELECTRICITY MARKET

S. You* **C. Træholt*** **B. Poulsen****

* Dept. of Electrical Engineering
Technical University of Denmark
2800 Kgs. Lyngby, Denmark
Email: {sy, ctr}@elektro.dtu.dk

**Dept. of Informatics and Mathematical Modeling, DTU
2800 Kgs. Lyngby, Denmark
Email: bjp@imm.dtu.dk

ABSTRACT

The emergence of Virtual Power Plant (VPP) can be attributed to the major boost of distributed energy resources (DER), which satisfies the changing needs of modern society on energy industry. Based on this concept, DER units disregarding the differences in their individual technology are loosely aggregated with a unique interface to the external grid and the energy market. This paper gives a brief overview of state of the art of the VPP technologies and proposes a generic VPP (GVPP) model running under liberalized electricity market environment. An attempt is made to provide an outline of the main functions that are necessary for the efficient operation of the GVPP. By utilizing the developed function-based platform, GVPP developers with different system requirements are able to get the most flexibility out of the GVPP model. A case study shows how a broker GVPP is developed based on the selection of appropriate functions.

1. INTRODUCTION

The traditional delivery of electricity from large, centrally controlled power plants is presently being complemented or even substituted by distributed energy resources (DER) due to the improved efficiency, higher flexibility and environmental friendliness of the latter [1]. However, along with their merits, these customer-side located energy resources are creating new and challenging issues related to both technical and economic aspects.

Technically, the DER units installed until now are mostly operated without coordination or remote control, feeding in a maximum possible generation. This may result in unexpected congestions when the generation capacity in one area exceeds the local demand and incurs reversed power flow [2].

Economically, many DER are deployed as “fit and forget”. In other words, today the potential of replacing conventional power plants with the increased number of DER units is not exploited at all. Further, regarded as resources with small generation capacity, the DER is generally prohibited from entering the present electricity market [3]. While most of the grid activities are coupled with different market products in today’s liberalized electricity market, this barrier to a great extent limits the potential benefits of DER.

One way to address the above issues is to aggregate a number of DER units in a so-called Virtual Power Plant (VPP). In this construction, the group of DER units will be directly/indirectly controlled to achieve certain objectives. The aggregation can be guided by functional needs, geographical locations, the nature of generation technologies or other kinds of commonalities.

Rather than dwelling on any specific kind of VPP, this paper proposes a model named Generic Virtual Power Plant (GVPP) which generalizes the targets and the architecture of the VPP. Further, by applying a function-based design method, a function-based GVPP platform can be obtained providing high flexibility to generalized VPP developers to meet their various needs.

This paper is organized as follows. Section 2 reviews the current VPP technologies. Section 3 elaborates on the concept of GVPP and its main features. Section 4 presents a functional designed approach to GVPP. Section 5 presents a case study wherein a broker-like GVPP is developed via selecting the appropriate functional modules. Section 6 concludes this work.

2. REVIEW OF VPP TECHNOLOGIES

The VPP-like configuration was conceptualized as Virtual Utility (VU) in [4] in 1997, which is a flexible collaboration of independent, market-driven entities that provides efficient energy service demanded by consumers without necessarily owning the corresponding assets. After recognizing the merits of DER, further developments based on the VU have been made in literatures and filed tests in order to address the ensued issues. The differences between the different developments are in the choices of DER technologies (i.e. fuel-cell based VPP and virtual biogas power plant, etc.), in desired activities (i.e. energy trading, grid support, etc.) and in control strategies (i.e. direct controlled VPP and indirect controlled VPP, etc.).[5] As the first two choices, the technology based and the activity based have to rely on their control strategies, thus the control strategy appear to be generic in another level above the former two. Basically all the present VPPs can be categorized in three groups according to what control strategy is implemented: direct controlled VPP, indirect controlled VPP and a mix of the two control strategies.

Direct Controlled VPP: performs a direct control over its portfolio of designated DER units based on all available information, such as market price, contract types, available transmission capability etc. The whole group of DER units is thus operated optimally to some extent, depending on the intelligence level the VPP aggregator. Although other studies [6] have shown that the DER resources in ideal conditions (such as precise weather forecasting and no sudden changes) can be coordinated very well according to predefined plans, the disadvantages of a direct controlled VPP, such as scalability and adaptability are obvious.

Indirect Controlled VPP: uses incentives like variable pricing concerning both generation and consumption to encourage the DER units to decide locally on whether or not to participate/connect. The aggregator, in this case, can still achieve a degree of controllability by varying the incentives of energy production or consumption based on statistical information, production and consumption forecasting and accumulated experience with incentive based behavior. Price-based control methods [5] and agent-based market-oriented algorithms [7] are good examples of such indirect control strategies utilized in the VPP, however there exists no published or written guarantee of the quality of the services delivered by such VPPs. Further, the income of the individual DER owner has to rely on the intelligence level of either the human being or the local controller of his unit.

A mix of the direct controlled VPP and the indirect controlled VPP can simply be regarded as a hierarchical structure wherein direct control and indirect control reside at different levels in order to maximize the value of the given communication and calculation resources.

Although there has been no consensus on how to aggregate the DER into a VPP framework in the best way, it is well understood that such aggregation service is necessary for facilitating a large-scale integration of the DER in the current/ future power system.

3. GENERIC VIRTUAL POWER PLANT

Instead of proposing a specific framework of a VPP composed of specific DER technologies, a more general concept so-called generic VPP (GVPP) is suggested in this paper. Compared with an individual VPP technology, the GVPP has its unique but generic characteristic: trading in the electricity market, through a function-based design on the basis of a generic architecture which welcomes all DER technology.

The GVPP is a market-oriented entity and it aggregates and coordinates a great number of DER units, with the intention of being an eligible electricity market player by supplying the qualified market products. As the overall activities of the GVPP are correlated to the corresponding tradable market products of different time scales, the energy resources within the GVPP are allocated efficiently in order to avoid economic losses incurred during the process of trading. Meanwhile, the diversity of market rules and market products, to a great extent, define the requirements of a GVPP.

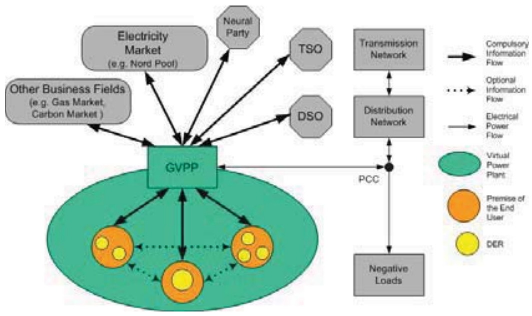

Fig. 1. Architecture of the Generic VPP

Even though the GVPP does not rely on any particular control strategy, it does have a generic architecture as given in Fig. 1. The DER units installed at different premises communicate with the GVPP bidirectionally through a common interface. Communication between every premise is possible if permitted by the technology and the regulatory framework. To the internal entities, the GVPP can act in different roles such as controllers, brokers or even traders on an ownership basis or a requirement basis. To the external entities, the GVPP appears as one legal body/representative which straightens out all the issues going with market transactions. A neural party may provide GVPP the necessary services e.g. metering, general authorization, financial validation/authentication and etc. In principle, the GVPP has to supply energy or services to the grid via a PCC (point of common coupling) where the quality of services can be measured; however, there can be many PCCs of a single GVPP when the DER units are aggregated over a large geographical area. In terms of grid security, a tight connection between GVPP and the grid operators (TSO/DSO) might have to be maintained, depending on the obligations that a GVPP has to fulfill.

As consequence of its property of being a generic framework which maintains the openness to all the existing VPP technologies, the GVPP requires a function-based design. A set of functions have to be assigned to different functional modules respectively with respect to fulfilling varying tasks. The loose couplings between each functional module grants more flexibility to the VPP developers who have different desires with respect to their varying capital resources and varying environments.

4. FUNCTION-BASED DESIGN OF GVPP

In this section, a function-based design approach is applied to design and develop a GVPP. As given in figure 2, all the DER units are linked to GVPP by an integration interface which builds up the communication channels between the GVPP and every DER. This interface can be developed according to IEC 61850-7-420, which standardizes the definitions of logical nodes of different DER technologies to increase the communication combinability [8]. The services that are collected in green blocks, named GVPP infrastructure, as a whole formulate the backbone of the entire system. The five functional modules, categorized by their application purposes, are interconnected by the GVPP infrastructure. As each functional module comprises several functional blocks in orange which further split the functionality of each functional module, the entire system becomes quite flexible. Individual functional blocks or a set of blocks even under different functional modules can be easily plugged in or out.

A. GVPP infrastructure

The GVPP Infrastructure provides the software foundation of the entire system. It has to be applied with open interfaces for both internal functional applications and their party applications, and to guarantee the reusability of a set of basic services which include:

- Configuration services;
- Archiving services;
- Reporting services;
- Messaging services;
- Logging services;
- Calculation services;
- Database services;
- Alarming services;
- User interface services;
- Security services;

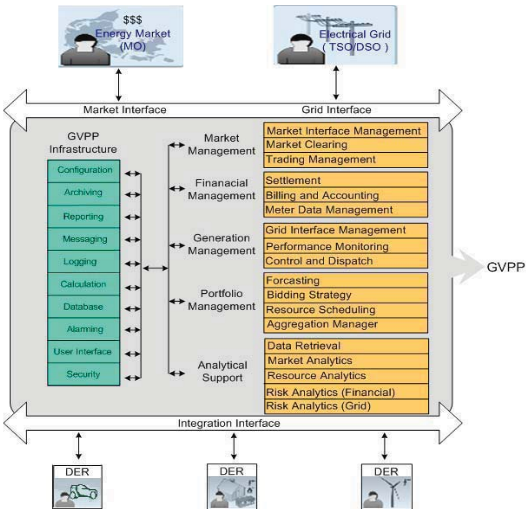

Fig. 2. Function-based Design for the GVPP

All the other functional modules can invoke the associate services whenever the need arises.

B. Market Management

The Market Management module is one of the key modules of a GVPP. It provides the market interface between the GVPP and all the energy markets from wholesale to retail. When the GVPP itself turns into a market operator, this module also provides the GVPP operator the necessary tools to manage the internal market. In general, there are three sub-functional blocks within this module:

1) Market Interface Management: This functional block, as the name implies, handles the interface complexities invoked by the diversified market commodities (energy, ancillary services etc.), varying market trading protocols (long term, short term, pool and bilateral etc.) as well as the communication requirements. Through this module, the GVPP should be able to smoothly interface with all kinds of energy markets in all possible trading packages.

2) Market Clearing: Differing from other market participants, the GVPP is an entity which may contain tens of thousands DER. As one of the possible management methods is to organize an internal market, wherein the DERs can submit their bids and offers following the internal market rules, the market clearing service maybe necessary.

3) Trading Management: The trading management function block, following the Market Interface Management function, provides a systematic management of dealing process. It also collects the related data information which is later used by other modules.

C. Financial Management

The Financial Management module provides the necessary tools to assure a reliable money flow which tracks every market transaction. It also includes three sub-functional blocks to complete this functional requirement.

1) Settlement: The settlement function is used to complete the post-trade process by generating all the settlement statements, invoice requests and reports. It has to be capable of handling both standard data input (e.g. customer information, contract type etc.) and dynamic data input (e.g. bids, awards, metered values etc.) in an accurate way. The ability of collating discrepancies with other parties is also necessary.

2) Billing and Accounting: This function manages the business accounting information and generates the financial reports that can be viewed by the corporate users of GVPP and individual customers. Meanwhile, it manages the billing activities conveniently.

3) Meter Data Management: This function helps the GVPP to manage the ever-increasing volumes of metered data before letting the metered data flood into the settlement process. In addition, it creates a view of energy flow and decrease data complexity (data aggregation/mining).

D. Generation Management

The Generation Management module contains a set of applications which supervise and performs direct control or indirect control over the DER assets from planning stage to real time operation. But in general, this module has to include at least three sub-functions.

1) Grid Interface Management: As the DER assets are distantly distributed in the electrical grid, the GVPP has to define a set of network points from where the services of GVPP can be provided to the grid and later on be evaluated. This function facilitates the indentation of such network points between the GVPP and the grid operator, and guarantees such services provided by GVPP comply with the grid code.

2) Performance Monitoring: This function carries out the real time communication between individual DER and the GVPP. Another possible communication channel would be the one between a local GVPP and the global GVPP when a hierarchical structure is formulated. Data collected from all the real-time measurement or supervision (e.g. real time power output of individual DER), as well as the aggregated generation/load profiles measured at PCCs are promptly dealt with by this function and transferred to the function module of control and dispatch.

3) Control and Dispatch: The control and dispatch function performs the control functionality over DER assets in either direct orders or indirect orders which depend on the GVPP control strategies. In the case of a centralized controlled GVPP, this function carries out economic dispatch functions which give out the exact generation settings for each DER. In the case of a price signal controlled GVPP, wherein the GVPP regulates the price signals to trigger the generation of every DER, this function is in charge of distributing price signal. In the case of grid emergencies, this function executes direct control orders in accordance with the pre-defined emergency schemes.

E. Portfolio Management

The portfolio management module intends to maximize the profits by managing the overall portfolio of GVPP in the best way from resource scheduling to bidding in the market. To meet this objective, the portfolio management module has to include:

1) Forecasting: The forecasting function contains a set of applications related to different forecasting objects, e.g. weather, energy demand, market conditions and even the aggregated customer responses to different stimulating schemes. Forecasting methods can be briefly categorized into two groups which are based on linear time series analysis (e.g. autoregressive models, regression models) and nonlinear time series analysis (e.g. neural network models, support vector machines]) [9] respectively.

2) Aggregation Manager: The aggregation manager is a functional block which provides different aggregation methods to the GVPP developers when they want to select an aggregation method complying with their local conditions. These methods could be aforementioned ones implemented through direct control or indirect control or even a combination. In real time, this function utilizes the selected control strategies to make appropriate decisions.

3) Resource Scheduling: This functional block determines the optimal schedules for resources especially in the context of centralized control. Traditional methods, e.g. dynamic programming, two stage optimizations [10] etc., which are used to

manage the unit commitment problem from short term to longer term can serve the needs of this function. In the case of a GVPP running decentralized control, this function may be carried out by signing different types of contracts with the DER owners, such as contracting the DER as balancing reserve etc., in order to reach an optimal generation profile.

4) Bidding Strategy: As the present electricity market is more or less an imperfect competitive market, the generators can bid for a price that is different from its marginal cost. This function therefore deals with different bidding strategies and determines the best settings. A survey of different bidding strategies are given in [11].

F. Analytical Support

This module provides an extensive analytical support to the GVPP, in order to achieve the objectives of providing data analysis support to other functional modules (especially the portfolio management module) and consummating the GVPP services by a continuous data mining. Five sub-function blocks form the entire function.

1) Data retrieval: In addition to interfacing with different databases, either internal ones or the third parties', this function also provides other services like data classification and data cleansing, which facilitate the use of data by other analytical functions.

2) Market Analytics: This functional block investigates the hidden patterns of the historical market performances regarding price variation, energy demand variation and the competitors' behaviors etc. When the GVPP operates an internal market to manage the DER, this functional block also provides necessary analysis on the internal market performance, based on which the internal market rules can be evaluated and improved. Market risks concerning price risks, quantity risks are also analyzed by this function.

3) Resource Analytics: The diversification of DER technologies results in a great complexity when the aggregation is carried out under a liberalized market condition. Such functional block investigates the performance of both individual DER technology and aggregated generation profiles according to different market environments. A great number of simulations and statistical analysis form the foundation of this function. The analytical results will benefit other functional modules such as aggregation manager and resource scheduling etc.

4) Risk Analytics (Financial): This functional block particularly analyzes the risk related to financial liquidity of the developed GVPP. Further, it proposes the risk controlling methods to GVPP operators.

4) Risk Analytics (Grid): As a generation entity comprising a great number of DER, the GVPP may cause congestions in distribution system. In general, it is the responsibility of the DSO to monitor and solve such issues. In case of grid emergencies such as black out takes place, the GVPP also needs to response immediately according to the either predefined emergency strategies e.g. islanding operation, or following the command of the DSO. Since the GVPP also faces the possibility of evolving into a utility, it may require analysis concerning security of the distribution system in the future. This functional block therefore meets such needs by running simulations of the local grid under severe conditions and presents the solutions.

5. CASE STUDY

This case study presented in this section aims to illustrate how to use the developed function-based platform to develop an individual GVPP when individual needs have to be met.

A broker-like GVPP system aims to develop an aggregated trading profile of a number of DER in the day-ahead electricity market of Nordpool [12]. It first generates the hourly bidding blocks for the next day based on its predictions. When delivery time approaches, the broker GVPP adjusts price signals in every minute to obtain the amount of energy delivered in real time as close as possible to the accepted bids. A detailed description of the control logic is given in [5]. All the DER participated in such system are assumed to be price responsive units. The broker GVPP, like many other generation companies, is exempt from grid security related obligations. Even though, the broker GVPP maintains a persistent cooperation with the local DSO, preparing to support requested services in case of grid emergencies.

Apart from the integration interface and the GVPP infrastructure which constitute the system foundation, Table 1 lists out the priorities of the functional modules required by such broker GVPP.

To further clarify the working flow of such a broker GVPP system, an information flow diagram linking the required functional modules is developed and given in figure 3. Functions like settlement, billing and accounting, are not included in figure 3 to avoid complexity, as they are post-trading procedures which do not influence the decision making. As indicated in figure 3, day-ahead trading is carried out following the direction of the hollow arrow which starts from the analytical module and ends with the generation schedule. In real time, the price signal control algorithm is implemented as a closed loop control, aiming at making the real time generation comply with the schedule. Communication between DSO and the GVPP is maintained if needed.

Table 1: Function Selections of the Broker GVPP

Functions		Priority	Specification
Market Management	Market Interface Management	Mh.	Includes an external Interface with the day-ahead market of Nordpool.
	Market Clearing	Nr.	This is only required when the GVPP operates internal markets.
	Trading Management	Mh.	Generates the bidding block and handles bidding procedure in the day-ahead market of Norpool.
Financial Management	Settlement	Mh.	Generates statements, reports etc.
	Billing and Accounting	Mh.	Carries out bookkeeping, accounting activities while generates and distributes bills/awards to individual DER owner.
	Meter Data Management	Mh.	Aggregates the individual DER outputs in real time.
Generation Management	Grid Interface Management	Mh.	Defines the PCC wherein the energy delivered by GVPP can be measured and assessed. This can be achieved with the cooperation of local DSO who has the entire knowledge of the local grid.
	Performance Monitoring	Mh.	Monitors the real-time value of the aggregated output of GVPP at the PCCs as well as the real time metered value of individual DER output.
	Control and Dispatch	Mh.	Distributes price signal to all DER units every minute.
Portfolio Management	Forecasting	Mh.	Predicts both hourly price for next day and the aggregated DER behaviors against price signals
	Bidding Strategy	Nth.	Including this function can increase the profit margin and lower the risk level of energy unbalance; however, this is not compulsory.
	Resource Scheduling	Nth.	Including this function can help the GVPP have a more economic generation profile, but this is not compulsory.
	Aggregation Manager	Mh.	Decides the aggregation method which is price signal and generates the price signal as well follow the control algorithm.
Analytical Support	Data Retrieval	Mh.	Supports other analytical function blocks.
	Market Analytics	Mh.	Supports the forecasting function.
	Resource Analytics	Mh.	Supports the forecasting function.
	Risk Analysis (Financial)	Nth.	This function could be achieved by a third party, thus not be compulsory in the GVPP framework.
	Risk Analysis (Grid)	Nr.	

(Mh. = Must have, which formulates the backbone of the GVPP system; Nth. = Nice to have, which can improve the efficiency of such system; Nr. = Not relevant for this case)

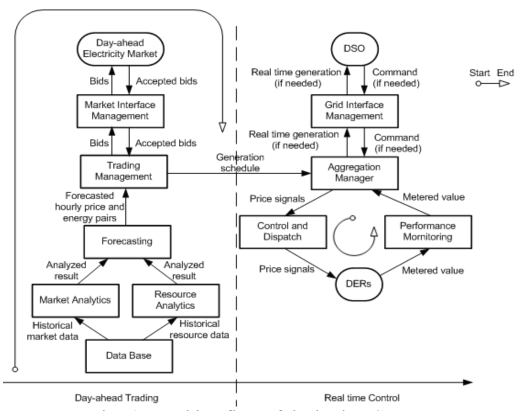

Fig. 3. Working flow of the broker GVPP

6. CONCLUSIONS

Building the next generation of frameworks which can adopt a large number of DER requires a mixture of new technologies and existing technologies deployed in an optimal and adaptive way. Rather than focusing on an individual VPP technology, this paper proposes a GVPP model which meets the different requirements of the VPP developers via applying a function-based approach to designing the VPP. This provides the VPP developers with flexibility towards the available tools/methods, and adaptability to different surroundings. The case study presented in the paper offers the readers a more intuitive illustration of how to use the GVPP function platform.

7. REFERENCES

[1] ENIRDGnet. : ‘Concepts and Opportunities of Distributed Generation: The Driving European Forces and Trend’, ENIRDnet Project deliverable D3, 2003.

[2] C. Yuen, D. Botting, A.D.B. Paice. : ‘When grids get smart’, Journal of ABB Review, 1/2008, pp.44-47.

[3] S. Ropenus, K. Skytte. : ‘Regulatory Review and Barriers for the Electricity Supply System for Distributed Generation in the EU-15’, International Journal of Distributed Energy Resources, Vol.3, 2007, pp.243-257.

[4] S. Awerbuch, A. Preston. : ‘The Virtual Utility: Accounting, Technology & Competitive Aspects of the Emerging Industry ’, published by Springer, 1997.

[5] S. You, C. Træholt, B. Poulsen. : ‘A Market-based Virtual Power Plant’, International Conference on Clean Electrical Power, Capri, 2009.

[6] R. Caldon, A. Rossi, R. Turri. : ‘Optimal Control of a Distribution System with a Virtual Power Plant ’, Bulk Power System Dynamics and Control-VI, Italy, 2004.

[7] J.K. Kok, C.J. Warmer. : ‘PowerMatcher: Multi-agent Control in the Electricity Infrastructure’, AAMAS-05, Utrecht, 2005.

[8] Cleveland, F.M. : ‘IEC 61850-7-420 communications standard for distributed energy resources’, Power and Energy Society General Meeting-Conversion and Delivery of Electrical Energy in the 21st Century, 2008.

[9] Makridakis, Wheelwright and Hyndman.: ‘Forecasting: Methods and Applications ’, published by WILEY, 1998.

[10] C.Weber. : ‘Uncertainty in the Electric Power System: Methods and Models for Decision Support’, published by Springer, 2004, pp.126-128.

[11] A.K. David, Fushuan Wen. : ‘Strategic Bidding in Competitive Electricity Markets: a Literature Survey’, XXXTrans. In Proc. IEEE PES Summer Meeting, Vol.4, 2000, pp.2168-2173

[12] http://www.nordpoolspot.com/

Is micro-CHP Price Controllable under Price Signal Controlled Virtual Power Plants?

Shi You, *Student Member, IEEE*, Chresten Træholt, and Bjarne Poulsen

***Abstract*— As micro-combined heat and power (micro-CHP) systems move towards mass deployment together with other kinds of distributed energy resources (DER), an increasing emphasis has been placed on how to coordinate such a large diversified DER portfolio in an efficient way by the Virtual Power Plant (VPP) like aggregators. Compared to the centralized direct control scheme, a decentralized control scheme "control-by-price" is proposed for the VPP operation. The corresponding scheme has advantages in scalability, transparency and simplicity. In this context, a short term economic analysis is conducted for three different micro-CHP systems to investigate the feasibility of being controlled by price. Such analysis is relevant for both controller designs for micro-CHP systems and VPP related operations. The results indicate that controlling the micro-CHP systems by price is feasible but could result in jumpy responses.**

***Index Terms*-- control-by-price, Distributed Energy Resources, micro-CHP, Virtual Power Plant**

I. Introduction

The micro-CHP technology has been identified as a significant element in fulfilling the energy efficiency and environmental aspirations worldwide, whilst tens of thousands of micro-CHP systems have already been successfully deployed in Europe in recent years [1]. These micro-CHP systems are believed to bring more value-added benefits to the power system operation if they can be coordinated under a Virtual Power Plant (VPP) like framework [2], which represents a flexible portfolio of the distributed energy resources (DER), i.e. small scale generators, storage systems and responsive loads.

One mechanism available for the VPP to coordinate a great number of DER on different time-scales is to use a price signal, also known as "control-by-price" [3]-[4]. Based on a set of hypothesis such as time-invariant quadratic cost function for generators, non-declining marginal cost etc., controlling the power system with price signal is shown feasible. Compared to the centralized direct control, the decentralized control scheme "control-by-price" is more suitable for the VPP operations due to its advantages in scalability, transparency and simplicity [5]. However, as the price responsive characteristics of different types of DER are highly dependent on local context and may not fully comply with the hypothesis, the fundamental economic analysis for the DER is required to study the feasibility of "control-by-price". This analysis not only relates to the design of local DER controllers but also provides the VPP developers with a better understanding of the DER price responsive characteristics.

In this paper, we investigate the price responsive characteristics for three different micro-CHP systems based on cost and profit analysis. Reasons for choosing the micro-CHP systems for this analysis are due to a) their capability of delivering heat and electricity simultaneously making them different from conventional generators; b) their higher controllability compared to other intermittent DER technologies; and c) the existing massive utilization of the micro-CHP systems. In section II, the control-by-price concept is shortly reviewed. In section III, one possible structure of the control-by-price based VPP is proposed. In section IV, the cost and profit analysis for three different micro-CHP systems is conducted and analyzed. Section V concludes the paper.

II. Control By Price

The fuel cost of an independent thermal power plant generally accounts for the biggest part of the operation cost and is expressed by a quadratic function as in (1), since the incremental heat rate (MBtu/kWh) is most often modeled as a linear function of the power output (kW) of the unit [6]. The start-up cost and shut-down cost are not considered here, assuming that the corresponding values are much lower compared to the fuel cost.

$$C = (a + b \cdot P + c \cdot P^2) \cdot f \tag{1}$$

Where C is the operation cost ($/h), P is the net electrical output (kW) which holds constant in that hour, f represents the fuel price ($/kWh) and a,b,c are normally nonnegative coefficients.

In general, $c > 0$ so that the cost function is convex; $b > 0$ as it represents the fixed term of the incremental heat rate; and $a > 0$ that captures the no load cost. The marginal cost MC ($/kWh) of such thermal power plant, as expressed in

---

This work was supported by the Danish PSO contract 7572.

Shi You and Chresten Træholt are with the Centre for Electric Technology, Department of Electrical Engineering, Technical University of Denmark, Kgs. Lyngby DK 2800, Denmark (e-mail: sy@elektro.dtu.dkand ctr@elektro.dtu.dk).

Bjarne Poulsen is with the Department of Informatics and Mathematical Modeling, Technical University of Denmark, Kgs. Lyngby DK 2800, Denmark (e-mail: bjp@imm.dtu.dk).

(2), is derived by getting the first derivative of (1).

$$MC = \frac{dC}{dP} = (2 \cdot c \cdot P + b) \cdot f \qquad (2)$$

In Fig. 1, the marginal cost curve for this power plant is drawn. For the given operation limit $P_{\min} \le P \le P_{\max}$, the according marginal cost boundaries can be easily found.

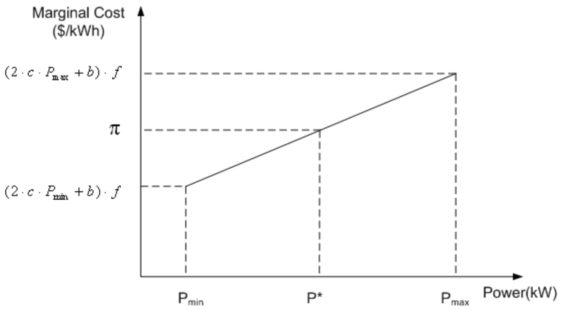

Fig. 1. Marginal cost for a thermal power plant

When a price signal π (\$/kWh), which lies between the marginal cost limits is sent to the generator by the system operator, the generator will operate at P^* in order to maximize its profit. However, because of the no-load cost, another condition to guarantee such positive response is to assure that the operation is profitable. Otherwise, the thermal power plant will not be started.

In light of the above analysis, the power system operator can control the power output of this generator by posting different price signals.

III. Price Signal Controlled VPP

In a VPP, the DER are aggregated in order to break the capacity barrier of the electricity market. Via market participation, the DER group can either operate in the more cost effective ways or provide specific services such as load following, load peak shaving, energy balancing and power balancing etc. to other entities [7]. As DER are typically in range of several to tens of kW, to reach a generation capacity level comparable to a conventional power plant requires hundreds to thousands of these small-scale units to be aggregated by a VPP. For the conventional centralized direct control, computation load and communication load is inevitably high for the VPP operation system. Alternatively, the "control-by-price" concept is more suited to control a large number of small-scale units as the computation load is distributed to every single DER and the information needed to be communicated between VPP and DER in real-time (e.g. every 15 minutes) is only the price signal while the metered response of the DER can be delivered to the VPP at a much lower frequency (e.g. once per day) to perform subsequent settlement. Apparently, this implementation considerably reduces the potential communication overhead of the two-way communication. With respect to providing services with different time requirements, the VPP can develop price signals at different time-scales (e.g. hourly price, 15-minute price) to keep the consistency. The DER owners are thus granted with more freedom in choosing the appropriate price schemes that best fit their DER characteristics and their comfort preferences. Further, the transparency level is also relatively high for the DER owners. Being the price takers, they can retrieve both the current price and the historical prices which support their decision makings.

In Fig. 2, one possible structure of the price signal controlled VPP is presented. The VPP server mainly comprises three functional modules: Prediction, Identification and Optimization. Once a service request is sent to the VPP, the Optimization module, which follows the pre-designed optimization algorithm, will decide and deliver a single or a series of price signals based upon the predicated information. This information include both the predicted local information e.g. the local electricity and heat demand of the DER group for the upcoming price controlled periods and the approximate price responsive characteristic of the DER group. The Prediction module and the Identification model are responsible for providing the corresponding information respectively. The derived price signals will be further delivered to the DER group to obtain the desired amount of generation. The individual DER i , based on the posted price signal and its local demand $P_d(i)$, will thus deliver the according generation $P_{gen}(i)$. As a result, the overall generation $\sum_{i=1}^{n} P_{gen}(i)$ of the VPP with n DER units will be delivered to fulfill the requested service.

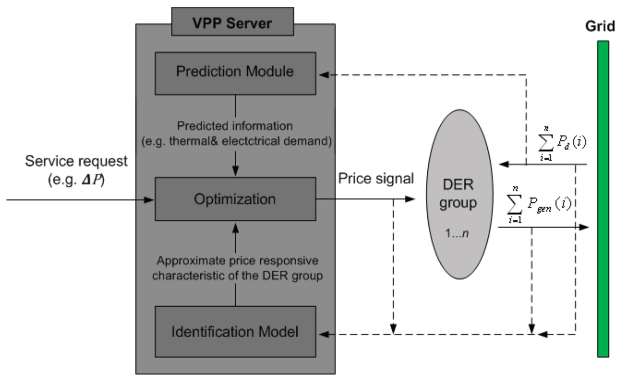

Fig. 2. Structure of a price signal controlled VPP

Compared to the direct control scheme, the difficulty of operating this price signal controlled VPP is much caused by the uncertainties of the price responsive characteristic of the DER group and the accuracy of the Identification model.

The price responsive characteristics of different DER technologies, which describe how each DER technology respond to different price signals, can be classified into three categories: cost based response, users' willingness based response and the response of the DER driven by the intermittent renewable resources. For DER technologies like the small-scale generators which have the specific operation costs to be recovered for a given period, their price responsive characteristics are dependent on the fuel price, generator efficiency and other factors e.g. start-up/shut-down cost, least-on/off time etc. In relative terms, the price responsive loads e.g. the freezers etc. and the storage technologies e.g. batteries for electric vehicles (EVs) etc. are more dependent on the users' willingness of shifting their consumption from a relatively high price period to a low price period. In the third category, the DER driven by intermittent renewable resources like wind turbines and PVs may response to any price signals due to their low operation cost. Still, all DER could have more complicated bidding strategies which may affect their price responsive characteristics [8].

To continuously improve the quality of the Identification model, the information of the price signal and the metered generation of the DER group as well as other necessary information such as local demand etc. can be recorded offline, as indicated by the dotted arrow lines in Fig. 2, and utilized for calibration of the Identification model and Predication model.

IV. Price Responsiveness of Micro-CHP Systems

The micro-CHP system, which could be driven by diversified prime mover technologies, is able to produce electricity and heat simultaneously to meet the local demand. As illustrated in Fig. 3, one typical setup of the micro-CHP system includes a micro-CHP unit, a thermal storage and an auxiliary boiler. For the internal combustion engine (ICE) based micro-CHP unit, a synchronous generator is driven by an ICE to produce electricity. The useful heat generated by this unit is mostly from the heat recovered from the engine jacket cooling water and the exhaust gas. The auxiliary boiler is often used as an alternative heat source; whilst the thermal storage is installed to further increase the flexibility of the micro-CHP system. For a grid-connected micro-CHP system, the electricity generated in excess could be fed back into the grid. When the electricity demand exceeds the local generation, electricity could be supplied by the external grid. In the case that a micro-CHP system is aggregated by a VPP, it is assumed that the generated electricity is sold to the VPP.

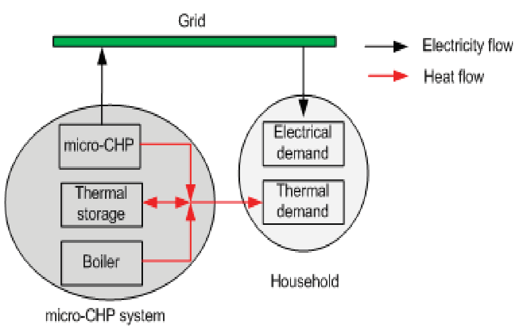

Fig. 3. Typical setup of micro-CHP system

Since the ICE based micro-CHP systems, being a mature technology, have already been massively deployed in Europe, they are the most probable candidates for VPP applications. Therefore, in the following part of this section, the price responsive characteristics of three different ICE based micro-CHP systems will be studied. The symbols used to describe the related information are given in Table I.

TABLE I
SYMBOLS USED TO DESCRIBE THE MICRO-CHP SYSTEMS

P_r (\$/h)	Hourly profit
C_{el} (\$/h)	Hourly electricity cost of micro-CHP unit
MC_{el} (\$/kWh)	Electricity marginal cost of micro-CHP unit
C_{th} (\$/h)	Hourly heat cost
f_{ng} (\$/kWh)	Price for natural gas
f_d (\$/kWh)	Price for diesel
π (\$/kWh)	Electricity price paid by VPP
η_{boiler}	Boiler efficiency
η_{el}	Electrical efficiency of micro-CHP unit
η_{th}	Thermal efficiency of micro-CHP unit
P_{elm} (kW)	Electrical output of micro-CHP unit
P_{thm} (kW)	Thermal output of micro-CHP unit
P_f (kW)	Fuel input of micro-CHP unit
$a_1, a_2, b_1, b_2, c_1, c_2$	Coefficients

A. 4-13kW$_{el}$ ICE-based Micro-CHP System

In Fig. 4, the steady state generation characteristic of the ICE-based XRGI13 unit made by EC Power A/S is approximated by means of polynomial fitting. The electrical operating range for such unit is 4-13kW$_{el}$, and the sampling data is from [9]. Such unit exhibits almost linear relationships between P_{elm} and the other two variables P_f and P_{thm} when it runs on natural gas. The according linear relationships are given in (3) and (4), for which the R-square correlation coefficients R^2 are both equal to 1.

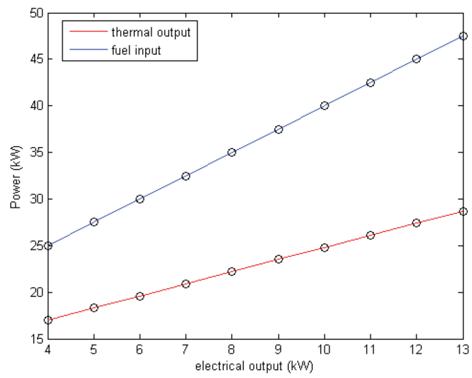

Fig. 4. Generation Characteristic of XRGI13 unit

$$P_{thm} = a_1 \cdot P_{elm} + b_1 \tag{3}$$

$$P_f = a_2 \cdot P_{elm} + b_2 \tag{4}$$

Wherein

$a_1 = 1.3, b_1 = 11.8, a_2 = 2.5, b_2 = 15$

Here, heat tank is assumed big enough to accommodate the excessive heat production. Whenever there is a certain heat demand, it can be covered by either the micro-CHP unit or the boiler. However, since the gas-fired boiler efficiency is normally above 75%, which is much higher than the thermal efficiency of the micro-CHP unit as shown in Fig. 5, the only way to make the micro-CHP production pay off is to sell the generated electricity to the VPP at a reasonable price.

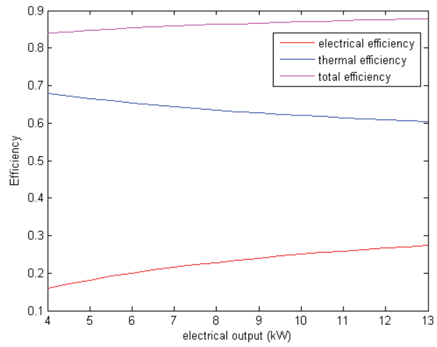

Fig. 5. Efficiency of XRGI13 unit

The cost function for the electricity generated by micro-CHP unit is expressed by (5), wherein the first part represents the fuel cost for the micro-CHP unit and the second part implies the cost for the boiler to produce the same amount of heat.

$$C_{el} = P_f \cdot f_{ng} - \frac{P_{thm}}{\eta_{boiler}} \cdot f_{ng} \tag{5}$$

By getting the first derivative of C_{el} and replacing P_f and P_{thm} with (3) and (4), the electricity marginal cost MC_{el} is found as expressed in (6).

$$MC_{el} = \frac{d(C_{el})}{d(P_{elm})} = (a_2 - \frac{a_1}{\eta_{boiler}})f_{ng} \tag{6}$$

Further, (7) has to be satisfied in order to guarantee the profitable generation of the micro-CHP unit. This constraint results in a price threshold, as given in (8), below which generating electricity by a micro-CHP unit is not profitable.

$$P_r = \pi \cdot P_{elm} - C_{el} \geq 0 \tag{7}$$

$$\pi \geq MC_{el} + \frac{f_{ng}}{P_{elm}} \cdot (b_2 - \frac{b_1}{\eta_{boiler}}) \tag{8}$$

As the boiler efficiency η_{boiler} to a great extent affects the price responsive characteristic of the micro-CHP unit, two different cases are investigated: η_{boiler} is 0.85 and η_{boiler} is 0.75. The price responsive characteristics of the micro-CHP unit for these two cases are illustrated in Fig. 6 and Fig. 7 respectively. In both cases, MC_{el}, represented by the blue curve, is constant and its value decreases as η_{boiler} decreases. In terms of the profitable price curve, represented by the red curve, it indicates the price threshold for the corresponding generation level. Below this threshold, start and operate the micro-CHP unit is non-profitable. For the first case where $\eta_{boiler} = 0.85$, the profitable price threshold declines as the P_{elm} increases, implying that the micro-CHP unit will only start when the electricity price is above $1.056 f_{ng}$ and work at its maximum electrical output $13kW_{el}$. For the second case when $\eta_{boiler} = 0.75$, the minimum profitable price is $0.5875 f_{ng}$ which is lower than the according MC_{el}. This implies that for a given electricity price $0.5875 f_{ng} < \pi \leq 0.77 f_{ng}$, the micro-CHP unit will work at its minimum output $4kW_{el}$. Once $\pi > 0.77 f_{ng}$, the micro-CHP unit will work its maximum electrical output $13kW_{el}$. In both cases, the scarce heat will be covered by the boiler while the excess heat production will be stored in the heat tank. As a result, the price signal can only partly control the electrical production of this micro-CHP system.

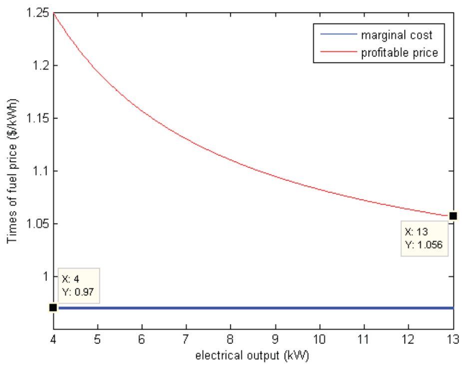

Fig. 6. Price responsive characteristic of XRGI13 unit when η_{boiler}=0.85

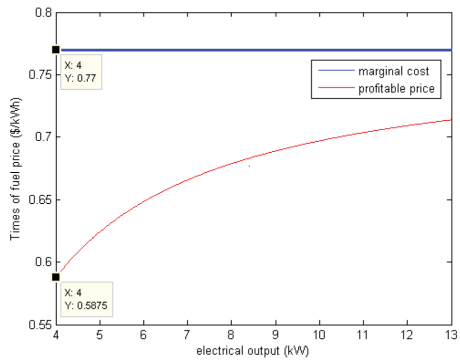

Fig. 7. Price responsive characteristic of XRGI13 unit when η_{boiler}=0.75

B. 1-9kW$_{el}$ ICE-BASED MICRO-CHP SYSTEM

In this section, the steady state generation characteristic of another $1\text{-}9kW_{el}$ ICE-based micro-CHP unit is simulated based on the sampling data given in [10]. This unit runs on diesel and the relationships between P_{elm} and the other two variables P_f and P_{thm} can be well represented by quadratic functions, which are listed in (9) and (10). R^2 are also equal to 1 for both functions. The modulating range of its electrical output is $1\text{-}9kW_{el}$.

$$P_{thm} = a_1 \cdot P_{elm}^{\ 2} + b_1 \cdot P_{elm} + c_1 \tag{9}$$

$$P_f = a_2 \cdot P_{elm}^{\ 2} + b_2 \cdot P_{elm} + c_2 \tag{10}$$

Wherein

$a_1 = 0.0835, b_1 = 0.4498, c_1 = 5.0595$
$a_2 = 0.0781, b_2 = 1.5619, c_2 = 7.1548$

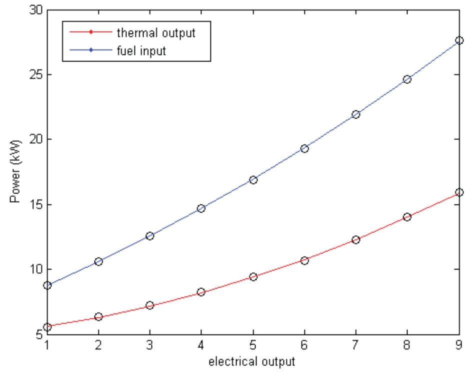

Fig. 7. Generation Characteristic of the 1-9kW$_{el}$ micro-CHP unit

Following the calculation procedures presented in case A, the electricity cost can be found as described by (11).

$$C_{el} = P_f \cdot f_d - \frac{P_{thm}}{\eta_{boiler}} \cdot f_{ng} \tag{11}$$

Accordingly, the electricity marginal cost and profit threshold of this micro-CHP unit are derived and given in (12) and (13) respectively.

$$MC_{el} = 2 \cdot (a_2 \cdot f_d - \frac{a_1}{\eta_{boiler}} \cdot f_{ng}) \cdot P_{el} + (b_2 \cdot f_d - \frac{b_1}{\eta_{boiler}} \cdot f_{ng}) \tag{12}$$

$$P_r = (\frac{a_1}{\eta_{boiler}} f_{ng} - a_2 \cdot f_d) \cdot P_{el}^2 + (\frac{b_1}{\eta_{boiler}} \cdot f_{ng} - b_2 \cdot f_d) \cdot P_{el} + (\frac{c_1}{\eta_{boiler}} \cdot f_{ng} - c_2 \cdot f_d) \geq 0 \tag{13}$$

Further, after assigning the diesel price $f_d = 1.5 f_{ng}$ and the boiler efficiency $\eta_{boiler} = 0.85$, the price responsive characteristic of this unit is found and given in Fig. 8.

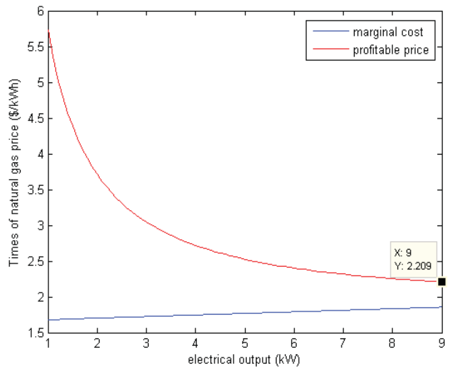

Fig. 8. Price responsive characteristic of the 1-9kW$_{el}$ micro-CHP unit when $f_d = 1.5 f_{ng}$

It can be seen that for this micro-CHP unit, MC_{el} rises as P_{elm} increases. Still, the micro-CHP units will not start until the price is above the minimum profitable value 2.209f_{ng}. As long as the price is above this value, the micro-CHP will work at its maximum electrical output.

By adjusting $f_d = f_{ng}$ and holding $\eta_{boiler} = 0.85$, another interesting case is presented in Fig. 9. As the diesel price is much lower compared to the previous case, the profitable price threshold is much lowered. Meanwhile, the lowered diesel price results in the declining marginal cost curve of the micro-CHP unit due to the much lowered heat cost of the micro-CHP. Further, only if the electricity price is higher than 0.9851f_{ng}, the micro-CHP will start and work at its maximum output.

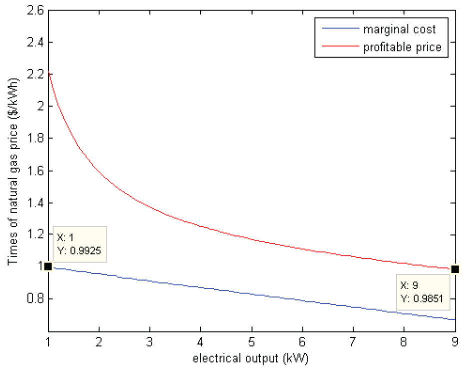

Fig. 9. Price responsive characteristic of the 1-9kW$_{el}$ micro-CHP unit when $f_d = f_{ng}$

C. Modified ICE-BASED MICRO-CHP SYSTEM

Although the electrical outputs of micro-CHP systems studied in case A and cases B are able to be modulated with direct control, the price signal control can hardly regulate their electrical outputs like what has been illustrated in section II. This is due to the formulation of marginal cost function and the profitable price threshold. These two factors are highly dependent on the inherent characteristics of the micro-CHP systems and the local contexts, such as the ambient temperature and altitude, coolant temperatures etc. which directly affects the combustion efficiency and the amount of recovered heat. In order to illustrate the possibility of using price signal to precisely regulate the electricity output of the micro-CHP unit, the generation characteristic of the 1-9kW$_{el}$ micro-CHP unit studied in Case B is re-simulated. In this case, the relationship between P_{thm} and P_{elm} is represented by a linear function as show in (14) and R^2 is now 0.9893, while the relationship between P_f and P_{elm} remains the same as (10).

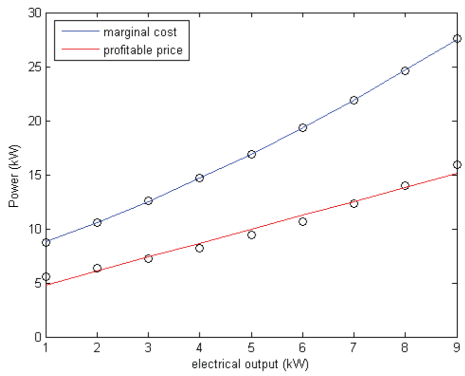

Fig. 10. Generation characteristic of the resimulated1-9kW$_{el}$ micro-CHP unit

$$P_{thm} = a_1 \cdot P_{elm} + b_1 \quad (14)$$

Wherein

$a_1 = 1.2853, b_1 = 3.5278$

Following the previous procedures, and also assume $f_d = f_{ng}$ as well as $\eta_{boiler} = 0.85$, the price responsive characteristic of the simulated 1-9kW$_{el}$ micro-CHP unit can be drawn in Fig. 11. The minimum value of the profitable price is $1.019f_{ng}$ corresponding to P_{elm} of 6.2kW. Because MC_{el} in this case rises linearly with increasing P_{elm}, for each price signal lying between $1.019f_{ng}$ and $1.456f_{ng}$ the electrical production of the micro-CHP system will then exactly follow the corresponding P_{elm} found from MC_{el} curve in order to maximize its profit. Once π is greater than the maximum value of MC_{el}, which is $1.456f_{ng}$, the micro-CHP will work at its maximum generation. In all, by sending appropriate price signals, the VPP can precisely regulate the electrical generation of this micro-CHP from 6.2kW$_{el}$ to 9kW$_{el}$.

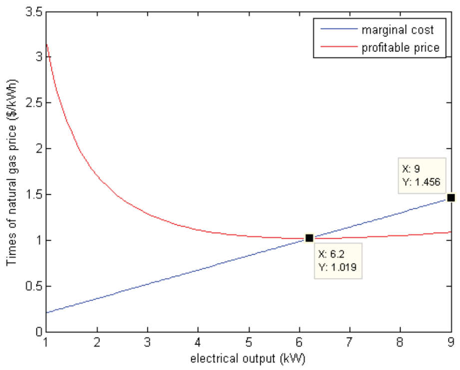

Fig. 11. Price responsive characteristic of the re-simulated 1-9kW$_{el}$ micro-CHP unit when $f_d = f_{ng}$

V. Conclusion

The future power system will evolve into a more decentralized system, where a great number of DER will be deployed to complement or even replace the conventional central controlled power plants. One possible way to handle the complexity of managing such a huge diversified generation portfolio could be using a VPP framework with the so-called "control-by-price" operation scheme. In this paper, one possible structure of the price signal controlled VPP is proposed. This semi-open loop controlled VPP has its advantages in scalability, transparency and simplicity. If the computation or communication overhead is not the primary concern, the proposed price signal controlled structure can be easily adjusted into a real time closed loop control, which may lead to more accurate and steady operation.

To better design and operate the price signal controlled VPP, the price responsive characteristics of different DER should be well studied based on the very basic cost and benefit analysis. Thus in this paper, the price responsive characteristics of three different ICE based micro-CHP systems are investigated. For the first two systems, the electrical output of the micro-CHP systems is very jumpy when the price signal control is applied. This can be more erratic when there are only a few micro-CHP systems being aggregated and a specific amount of power is required. For the third case, the electrical output of the corresponding micro-CHP system is able to track the price change in a certain range, providing a much better performance. Particularly, it can be easily found that different micro-CHP systems exhibit very different price responsive characteristics due to their inherent features and local conditions. Thus it would be possible for the VPP to provide services with relative stable electricity generation when a great number of diversified DER are aggregated and price controlled.

VI. Acknowledgment

The authors gratefully acknowledge the EC Power A/S for supplying the documents with sample data.

VII. References

[1] J. Slowe "Micro-CHP: Global Industry Status and Commercial Prospects," in *Pro. 23rd World Gas Conference*, pp. 1-9.

[2] D. Pudjianto, C. Ramsay, G. Strbac, "Virtual Power Plant and System Integration of Distributed Energy Resources", *IET Renewable Power Generation* vol.1, issue.1, pp. 10-16, 2007

[3] F.L.Alvarado, "Is system control entirely by price feasible?", in *Pro. 36th Annual Hawaii International Conference*

[4] F.L.Alvarado, "Controlling power systems with price signals?", *Decision Support System*, vol.40, issue 3-4, pp. 495-504, 2005

[5] S. You, C. Træholt and B. Poulsen, "A market-based Virtual Power Plant," in *Proc. 2009 International Conference on Clean Electrical Power*, pp. 460-465.

[6] A.J.Wood and B.F.Wollenberg, *Power Generation, Operation and Control*, Ed. New York: Wiley, 1984, pp.10.

[7] S. You, C. Træholt and B. Poulsen, "A study on electricity export capability of the micro-CHP system with spot price", in *Pro. 2009* Power *& Energy Society General Meeting*, pp.1-6.

[8] K. Kok, "Short-term Economics of Virtual Power Plant," in *Pro. 2009 20th International Conference on Electricity Distribution*, pp. 1059.

[9] B.Bogner, S.S.Abildgaard and J.R.Andersen "Power Distribution System," UK. Patent GB2402001, Sep. 20, 2006.

[10] J.R.Andersen "Method and Apparatus for Providing Heat and Power," World Intellectual Property Organization, Pub No. WO/2009/063212, May.22, 2009.

VIII. Biographies

Shi You received the B.Sc. degree in Electrical Engineering from Harbin Institute of Technology, China, and the M.Sc. degree in Electrical Engineering from Chalmers Institute of Technology, Sweden in 2004 and 2006 respectively. He is currently pursuing the PhD degree in department of Electrical Engineering at the Technical University of Denmark. His main fields of interest are renewable energy, smart grid and electricity market.

Chresten Træholt is an Associate Professor at Centre for Electric Technology, Technical University of Denmark. He received a PhD. in Material Science from the Technical University of Denmark in 1995. His main fields of interests are distributed generation, superconductor technology and superconducting cables.

.

Bjarne Poulsen is an Associate Professor of Department of Informatics and Mathematical Modeling at the Technical University of Denmark. He earned his PhD. in Electrical and Computer Engineering from The Technical University of Denmark in 1996, a master from Aalborg University in 1990.

Economic Dispatch of Electric Energy Storage with Multi-service Provision

Shi You, Chresten Træholt
Dept. of Electrical Engineering
Technical University of Denmark
2800 Kgs. Lyngby, Denmark
{sy,ctr}@elektro.dtu.dk

Bjarne Poulsen
Dept. of Informatics and Mathematical
Technical University of Denmark
2800 Kgs. Lyngby, Denmark
bjp@imm.dtu.dk

***Abstract*—This paper develops a generic optimization model that explores the difficulty met by Electric Energy Storage (EES) systems when economic dispatch for multiple-service provision is requested. Such a model is further used to investigate the economic performance of an EES system which meets the 10-minute balancing requirement and hourly load shifting opportunities in the Western Electricity Coordinating Council (WECC) area for a 2030 load scenario. Piecewise linear equations are used to represent the cost function of varying load. The results show that when EES is economically dispatched, to achieve multiple value streams could result in more saving than to provide single service.**

Keywords-Eelectric Energy Storage; economic dispatch;multi-service

I. INTRODUCTION

By converting electric energy into other forms, such as chemical, kinetic of potential energy, the electricity can be stored and drawn upon at a later time to perform useful operation. Based on these principles, advanced electric energy storage (EES) technologies are emerging as a potential resource to support the integration of intermittent Renewable Energy Resources (RES) and to provide cost-effective and reliable grid operation.

Pumped Hydro Storage (PHS) is the most widespread utility-scale EES with good performance characteristics (good roundtrip efficiency 55%-85%, low operation cost around 10000 €/MW/year and long life-time about 50 years) in use today. The response time of PHS is on a one minute scale if the turbine is standing still and 10 second if the turbine is initially spinning- allows PHS plants to deliver multiple services such as peak shaving, load leveling, load following, spinning reserve and more [1]. Another utility-scale EES technology that is currently available is the Compressed Air Energy Storage (CAES). In such a storage system, excess electricity is converted to compressed air and stored in a reservoir. In the mode of discharging, the air is released, heated via combustion together with fuel and is finally passed through a turbine. One example of CAES is a 290MW/3h plant in Huntorf, Germany. Among other services, the Huntorf CAES has also been used to balance wind power generation [2]. Unlike PHS and CAES with typical capacity above tens of MW, other EES technologies such as Batteries, Supper Magnetic Energy Storage (SMES), Hydrogen Fuel Cell Storage System (HFCSS) and Flywheels may be sized from several kW to hundreds of MW, which makes such technologies available for both utilities and their customers [3]. For small-scale EES applications like Electric Vehicles (EV), the EV owners only contributed to eliminate CO2 emissions when driving but also may benefit from the volatility of electricity prices by charging smartly. If numerous small-scale EES can be further efficiently aggregated into a Virtual Power Plant (VPP) like framework [4], providing value-added services to grid operation may be envisioned.

Many previous studies have presented optimal operation schemes for EES in hybrid applications, such as wind power with EES [5-6] and PV with battery [7] ect, in order to smooth out the intermittent nature of some RES. In [8-9], optimal generation schedules are developed for EES to provide specific services like load leveling and peak shaving. However, as the EES is able to perform multiple grid services at the same time, there is a need to develop efficient dispatch strategies which consider multi-service provision. Such strategies should run the EES at the maximum profit to reliably provide various services, recognizing the operational limits of the EES and services' requirements e.g. cycle time limit and capacity limit as well as the associated value for every service. This paper presents a generic deterministic optimization model of the EES that deals with this challenge. Main outputs of this model is an optimal operational plan for the EES charging/discharging as functions of every service requirements. When a long term study is carried out, the resulted economic performance of the EES is also useful to evaluate the outcome of different service combinations.

The paper is organized as follows: in Section II, the problem of economic dispatch of the EES with multi-service provision is formulated. In Section III, this model is used to investigate the economic performance of an EES system which meets the 10-minute balancing requirement and hourly load shifting opportunities in the Western Electricity Coordinating Council (WECC) area for a 2030 load scenario. A comparison is done between the economic benefits of providing the combined service versus a mere load shifting. Section IV concludes the paper.

II. MODELING THE EES SYSTEM

Generally speaking, the EES is a memory device and it becomes economical when marginal cost of electricity varies more than the accumulated costs of storing and retrieving,

This work was supported by the Technical University of Denmark (DTU) and collaborative partner: Pacific Northwest National Laboratory (PNNL).

including the energy lost in the process. From the system operator point of view, the aim of using EES in power system operation is to reduce the societal cost while meeting the system requirements. In other words, the profit, which can be represented by the cost difference between operating a power system without the EES and with the EES, has to be maximized. When multi-service provision is at request, the profit is the sum of the profit resulted from providing each service by the EES. This problem can be formulated as an optimization problem.

Assuming EES provides N types of services simultaneously, and t_i with $i \in 1...N$ represents the time cycle for service i, which may vary from seconds to days. In order to synchronize the time clock for different services, t' is used to denote the greatest common divider of t_i. For instance, if EES provides hourly load shifting and 10-minute balancing service at the same time, t' is found as 10 minutes. For all time steps $t' \in 0,1...T$, the EES must meet power balance and energy balance which are modeled by (1) and (2) respectively.

$$P(t') = \sum_{i=1}^{N} P_i(t') \tag{1}$$

$$E(t'+1) = E(t') + P(t') \cdot \Delta t \cdot \eta + l(\Delta t) \tag{2}$$

$$\text{where } \eta = \begin{cases} \eta_c & \text{if } P(t') \geq 0 \\ 1/\eta_d & \text{if } P(t') < 0 \end{cases} \tag{3}$$

In (1), variable $P(t')$ states the aggregated power charged/discharged by the EES at time step t', and $P_i(t')$ describes power provided by the EES to meet the individual power requirement of service i at that particular moment. Positive values of $P_i(t')$ represent the EES being charged to meet the requirement of service i and negative values indicate the EES being discharged. However, the symbol of $P(t')$ determines the final charging/discharging status of the EES. In (2), the non-negative variable $E(t')$ represents the energy stored by EES at the beginning of time step t' and Δt states the length of t'. The variable η, as indicated in (3), represents the function of charging/discharging efficiency η_c and η_d. When $t' = 0$, $E(0)$ therefore represents the initial energy stored by the EES. $l(\Delta t)$ represents the internal energy loss during energy storing over Δt. For different EES technologies, function $l(\Delta t)$ may vary quite a lot. EES technologies like underground pumped hydro systems display very low loss, since they are designed to be isolated from the outside. In opposite pumped hydro systems with its unsheltered reservoirs and extreme weather conditions may display a high internal loss. However, if the cycle time for the requested power system service is relatively short, the internal energy loss for advanced EES technologies will be relatively low and thus can be ignored.

The other constraints for modeling an EES include the power capacity limit and energy capacity limit which appears following in (4)-(6).

$$P(t') \leq P_{c\max} \quad \text{if } P(t') \geq 0 \tag{4}$$

$$|P(t')| \leq P_{d\max} \quad \text{if } P(t') < 0 \tag{5}$$

$$E_{\min} \leq E(t') \leq E_{\max} \tag{6}$$

where $P_{c\max}$, $P_{d\max}$, $E_{\min}$ and $E_{\max}$ represent the maximum power capacities for the EES charging and discharging and the minimum and maximum energy storage level respectively.

As mentioned before, the objective function is to maximize the profit of using EES to provide requested services over a certain time period. This function is expressed as

$$MaxSaving = \sum_{i=n}^{N}\sum_{t'=0}^{T} Cost_{ees}(i,t') - \sum_{i=n}^{N}\sum_{t'=0}^{T} Cost_{non-ees}(i,t') \tag{7}$$

where $Cost_{ees}(i,t')$ is the cost for providing the requested service i during time period t' using a power system with the EES and $Cost_{non-ees}(i,t')$ represents the corresponding cost for providing requested services using resources in the original power system. As the cost for providing different services are always valued in different ways, such as capacity pricing, energy pricing and so forth, the objective function may vary from case to case. Depending on how the cost function of each service provision is formulated, the EES model could be either linear or non-linear which results in different degree of complexities and accuracies of solving this optimization problem.

III. Case Study

In this case study, the aforementioned optimization model is applied to investigate the economic performance of an EES system which meets the 10-minute balancing requirement and hourly load shifting opportunities in the Western Electricity Coordinating Council (WECC) area for a 2030 load scenario. The WECC region covers 1.8 million square miles, all or part of 14 states, two Canadian provinces and a portion of Mexico. The 2030 load scenario of the WECC region predicated by Pacific Northwest National Laboratory (PNNL) has a peak load of approximately 190GW and the values of 10-minutes balancing signals between ±15GW introduced by the future increase of wind power penetration. The EES system, which represents an aggregation of all kinds of EES like facilities deployed in the WECC region, is assumed to be with an energy capacity of 30 GWh and a power capacity of 15GW for both charging and discharging in order to meet the required services. Further, a series of assumptions for the 2030 scenario are made as following:

a). The EES is the only balancing resource in this system therefore it has to exactly meet the 10-minute balancing requirement.

b). The power of the EES charged/discharged for load shifting is constant on an hourly basis.

c). The power of the EES charged/discharged for 10-minute balancing holds constant within every 10 minutes.

d). Balancing signals are not affected by the change of load profile. The up balancing signals that indicate generation deficit are assumed to be positive; while the down balancing signals that indicate the generation surplus are assumed to be negative.

e). The EES system is lossless.

f). Hourly Locational Marginal Price (LMP) is used to calculate the system cost of load serving.

g). Hourly LMP is assumed to be a piecewise linear function of hourly load.

h). The balancing cost is calculated as the amount of energy used for balancing multiplying the balancing price. The balancing price is assumed to be 40$/MW-hr constantly for both up and down balancing requirement during 2030.

A. *Problem Reformulation*

1) *Constraints*

Based on Based on assumptions (a)-(d), the power balance of the EES could be easily established for every 10 minutes (Δt) consecutively as shown in (8)-(10). In (8), variables $P_{load}(t')$ and $P_{balancing}(t')$ represents the power charged/discharged by the EES for shifting load and meeting balancing requirement respectively at time step t'. In (9), at time step t', the original system load $PD_{non-ees}(t')$ is changed into $PD_{ees}(t')$ when the EES gets involved to perform load shifting. Equation (10) follows assumption (a), ensuring the up and down balancing signals $PB_{up}(t')$ (positive) and $PB_{down}(t')$ (negative) are always met by discharging/charging EES.

$$P(t') = P_{load}(t') + P_{balancing}(t') \tag{8}$$

$$PD_{ees}(t') = PD_{non-ees}(t') + P_{load}(t') \tag{9}$$

$$P_{balancing}(t') = \begin{cases} PB_{up}(t') & \text{if } P_{balancing}(t') \le 0 \\ PB_{down}(t') & \text{if } P_{balancing}(t') > 0 \end{cases} \tag{10}$$

In terms of the energy balance of the EES as shown in (2), efficiencies for both charging and discharging become 100% under assumption (e); meanwhile the internal loss function $l(\Delta t)$ is neglected. Parameter values that constrain the power capacity and energy capacity of such EES are given in Table I.

TABLE I. LIST OF PARAMETER VALUES FOR THE EES SYSTEM

$P_{c\max}$	15GW	$E_{\min}$	0
$P_{d\max}$	15GW	$E_{\max}$	30GWh

As the EES is the only balancing resource in this model, the initial energy stored in EES is assumed to be 10 GWh for every optimization cycle in order to make sure the EES has enough energy to provide up-regulation services.

2) *Objective Function*

In this case study the cost functions expressed in (7) are comprised of two parts since the EES provides load shifting service and 10-minute balancing service together. While the costs for these two services have different formulations, it is explained separately in the following two sections 2-a and 2-b.

2-a) *Cost of Meeting the Load*

Generally the cost of meeting a certain load profile by a specific generation technology is dependent on the associated cost function. As WECC is an area containing various generation technologies, assumptions (f) are made to simplify this problem. This results in (11), which reflects the cost of meeting the hourly load profile.

$$Cost_{load}(t') = ED(t') \cdot LMP(t') \tag{11}$$

where $ED(t')$ represents the load at time step t' measured in MWh and $LMP(t')$ states a rate per MWh for that particular time step. Because $ED(t')$ changes when the EES performs load shifting as given in (9), a relationship between LMP and load has to be found to assess how much the LMP is affected by the involvement of EES. However, since LMP is theoretically calculated based on the system wide information rather than a single generation/load profile within that area, a loose coupling between the hourly LMP and load can only be found when the studied areas have adequate generation resources and play roles as energy exporters.

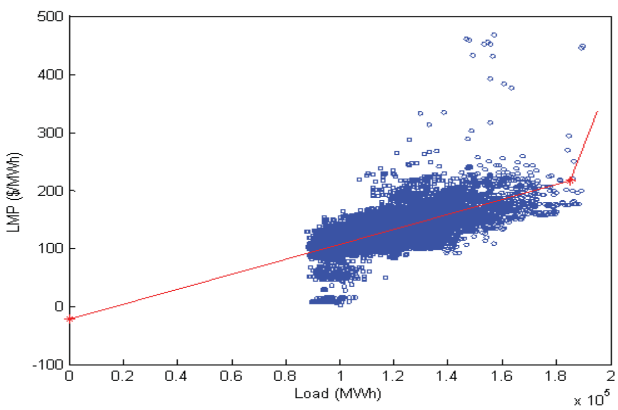

Figure 1. Representing the relationship between LMP and load for WECC with piecewise linear functions

As shown in Fig.1, the hourly LMP versus the hourly load profile predicted for WECC 2030 is indicted by the blue open dots. Such prediction is done by PNNL using PROMOD [10], a- state-of the-art production cost model based on extensive information of WECC. When the hourly load is between 90GWh and 185GWh the LMP increases gradually with increase of load. Once the hourly load exceeds 185GWh, the associated LMP increases more steeply. In order to reduce the complexity, this trend is modeled by a piecewise linear function given as the red line in Fig.1, using a smooth curve fitting. And the LMP is therefore only load dependent. The piecewise linear function representing this relationship is given in (12).

$$LMP(t') = \begin{cases} 0.0013 \cdot ED(t') - 22.23 & \text{if } ED(t') \le 1.85 \times 10^5 \\ 0.012 \cdot ED(t') - 2022.35 & \text{if } ED(t') > 1.85 \times 10^5 \end{cases} \quad (12)$$

The cost of the system for meeting the load at t' before and after including the EES is given in (13) and (14) wherein the energy consumption $ED(t')$ is calculated as the product of the power consumption in each case and the time length Δt with the unit of hour.

$$Cost_{load\_nonees}(t') = \frac{PD_{non-ees}(t') \cdot \Delta t \cdot LMP_{non-ees}(t')}{60} \quad (13)$$

$$Cost_{load\_ees}(t') = \frac{PD_{ees}(t') \cdot \Delta t \cdot LMP_{ees}(t')}{60} \quad (14)$$

2-b) Cost of balancing service

The cost of providing balancing services at t' is expressed in (15), wherein $PB_{balancing}(t')$ states the balancing price in the unit of \$/MW-hr. Given assumption (h), $PB_{balancing}(t')$ remains 40\$/MW-hr for both up and down balancing services. When an EES is assumed to fully provide such 10-minute balancing service, the saving is equal to the cost when variable cost is the only concern.

$$Cost_{balancing}(t') = \frac{|P_{balancing}(t')| \cdot \Delta t \cdot PB_{balancing}(t')}{60} \quad (15)$$

2-c) Overall saving

For all time-steps $t' \in 0,1...T$, the overall saving is expressed in (16). The objective function is thus to maximize the overall saving. Because the hourly LMP is modeled as piecewise linear equations, (16) turns into a non-linear function The Matlab nonlinear optimization tool box [11] is used in this paper to find the optimal solutions for this problem.

$$Saving = \sum_{t'=0}^{t'=T} Cost_{balancing}(t') + \sum_{t'=0}^{t'=T} (Cost_{load\_nonees}(t') - Cost_{load\_ees}(t')) \quad (16)$$

B. *Case Studies and Analysis*

The reformulated economic dispatch model is applied to investigate the economic performance of the simulated EES in both intraday analysis and annual analysis. In the Intraday analysis, the EES performances on two specific days of 2030: 1st of January and 14th of August are studied separately. The initial energy stored in the EES in both cases is assumed to be 10GWh in order to tackle the balancing requirement in the beginning of the day. The costs for the initial energy stored in EES in both cases are assumed to be 1.2 million \$, provided the LMP equals 120\$/MWh. Following that, annual economic performance of using EES to provide the referred two services is evaluated and further compared with the same EES providing load shifting service only.

1) Case 1 - 1st of January

In Fig. 2, 10-minutes balancing signals are shown in the solid blue line. While in most time of the day, the balancing signals are up signals which require the EES to operate in discharging mode.

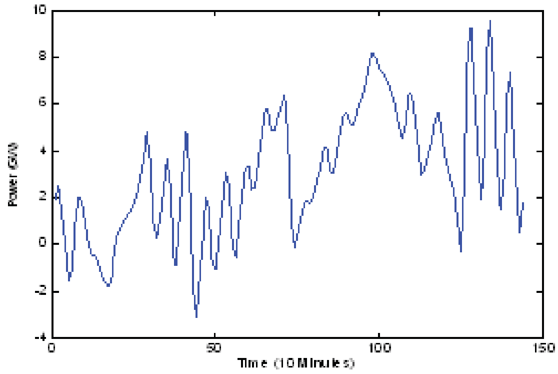

Figure 2. 10-minute balancing requirements of WECC on 1st of January

In Fig.3 the load profile versus hourly LMP of WECC on 1st of January is depicted. The peak load of the day given in the solid blue line takes place at 7pm priced by the highest value of LMP as shown in the dotted blue line. When the EES gets to perform load shifting, it can be found that the new load curve as given the red solid line has a lower peak value and a larger bottom value than the original load curve. By cutting the peak load, the cost of peak load hour is accordingly reduced as given in the red dotted line.

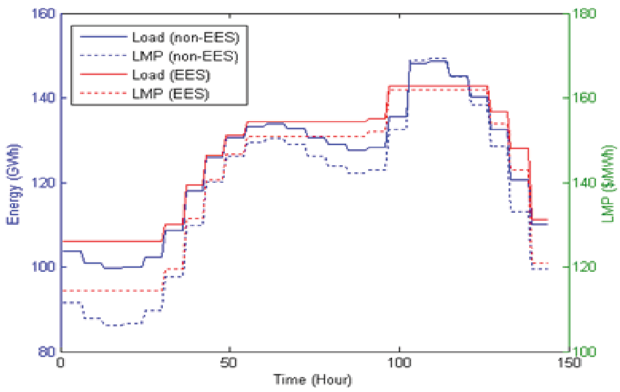

Figure 3. Load profile versus hourly LMP of WECC on 1st of January

The energy storage level and the power flow of the EES are depicted in Fig. 4. It can be found that the battery is first charged since the early morning balancing requirements are down signals and the energy cost LMP is relatively low. After the 100th 10 minutes, the EES mainly discharges. This is due to the high up balancing signal coming at that moment and the preparation for the later action of peak load shaving. When the peak load moment arrives, the power discharged by EES is much reduced as curtailing the load requires the EES to be charged. However, due to the relatively high up balancing requirements, the EES still works in discharging mode in most of the time till the end of the day.

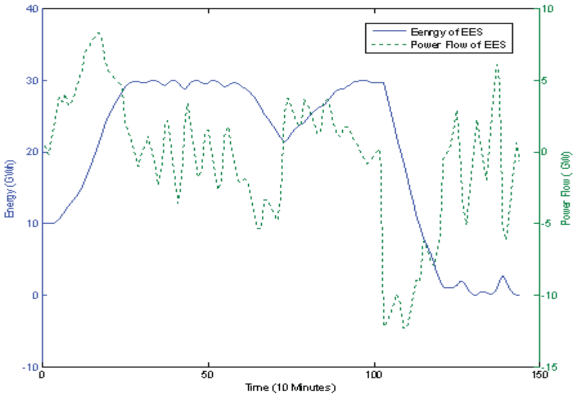

Figure 4. Energy storage level and power flow of the EES on 1st of January

The economic performance of the EES on 1st of January is given in Table II. It is found that the system cost is actually increased when having the EES to provide load shifting and balancing services. This is because on that day, the balancing signals are always up signals which require the EES to discharge. Even though there is energy initially stored in the EES, the EES still have to buy energy through load shifting service to meet the continuous up balancing requirements.

TABLE II. ECONOMIC PERFORMANCE OF EES ON 1ST OF JANUARY

	System(non-EES)	System (EES)
Load Cost ($ 1M)	420	437+1.2
Balancing Cost ($ 1M)	3.2	0
Total Cost ($ 1M)	423.2	438.2

2) Case 2 - 14th of August

In Fig. 5, 10-minutes balancing signals are shown in the solid blue line. Compare to the balancing signals on 1st of January, the signals on 14th of August are not always up signals.

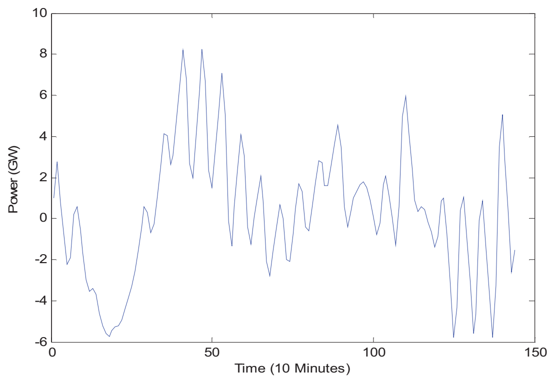

Figure 5. 10-minute balancing requirements of WECC on 14th of August

The load profile versus hourly LMP of WECC on 14th of August is given in Fig. 6. The peak load of the original load profile of the system without EES occurs at 5pm. As the peak load is larger than 185GW, the LMP for 5PM given in the blue dotted line is much higher than usual. The involvement of the EES successfully cut the peak load into a smaller value, resulting in a much lower LMP value for 5pm.

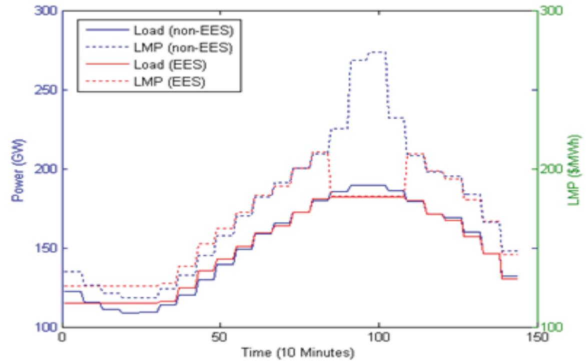

Figure 6. Load profile versus hourly LMP of WECC on 14th of August

The energy storage level and the power flow of the EES on 14th of August are depicted in Fig. 7. It is seen that the EES is first charged in the morning and then starts discharging when the peak load arrives. In the end of the day, the EES is completely empty in order to maximize the usage of its stored energy.

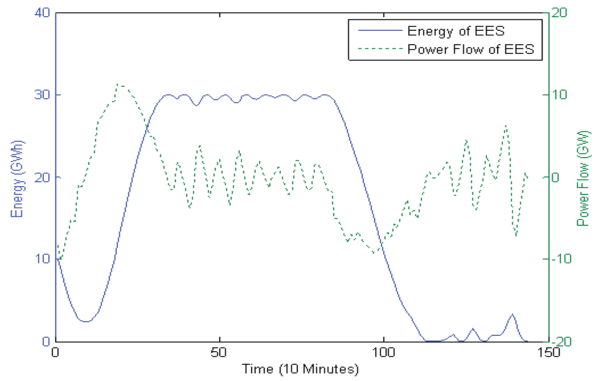

Figure 7. Energy storage level and power flow of the EES on 14th of August

In Table III, the comparison of total cost between the system with EES and without EES is given. Since the balancing signal requires the EES to charge and discharge almost evenly, the EES does not need to buy more energy when it provides load shifting services. Further, the reduction of peak load results in a relatively low value of LMP, which in turn brings in some benefits. Due to such reasons, the total cost is reduced from 667.3million $ down to 639.2 million $.

TABLE III. ECONOMIC PERFORMANCE OF EES ON 14TH OF AUGUST

	System(non-EES)	System (EES)
Load Cost ($ 1M)	665	638+1.2
Balancing Cost ($ 1M)	2.3	0
Total Cost ($ 1M)	667.3	639.2
Saving ($ 1M)	29.3	

3) Case 3 - Annual Economics of WECC system when the EES provides two services

Regarding the annual study, the optimization program for dispatching the EES is done on daily base due to the limited calculating resource. At the end of every day, the energy left in the EES is further assumed to be equal to the initial energy storage level 10GWh in order to guarantee there is enough power to meet continuous up balancing signals. The daily optimal dispatch is repeated for the whole year 2030. The annual cost performance is given in Fig. 8. The original cost for load serving and meeting balancing requirements are calculated for every month and depicted in blue bars and green bars, while the cost for meeting the load when the system includes EES is depicted by the red bars. Compared with the cost for meeting the hourly load, the balancing cost represents a small fraction of the original total cost. A summary of the annual cost for system with and without the EES is given in Table IV showing that the total savings by economically dispatch the EES for multi-service provision can yield 2570.46 million $ in 2030.

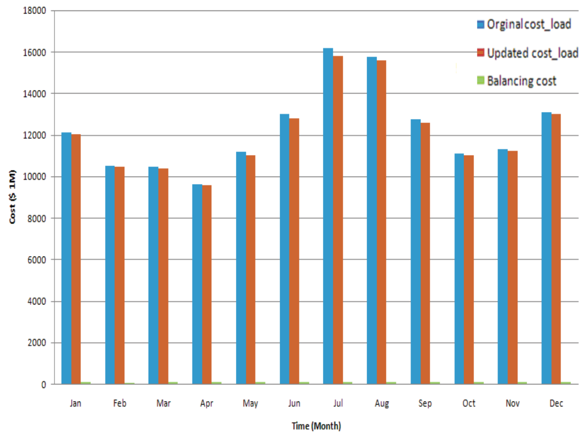

Figure 8. Annual cost performance for WECC system with the EES provides both load shifting and 10-minute balancing services for the year 2030

TABLE IV. ANNUAL ECONOMIC PERFORMANCE OF EES

	System(non-EES)	System (EES)
Load Cost ($ 1M)	147058.83	145394.2
Balancing Cost ($ 1M)	905.83	0
Total Cost ($ 1M)	147964.66	145394.2
Saving ($ 1M)	2570.46	

4) Case 4 - Annual Economics of WECC system when the EES provides only load shifting

When the EES only provides load shifting service, it has more flexibility on changing the original load profile. One example showing such difference on 1st of January is given in Fig. 9. Same as in Fig. 3, the peak load of the original load profile depicted in blue is reduced when the EES provides both load shifting and 10-minute balancing services. In the case that the EES provides only load shifting, the peak load is reduced to an even lower value depicted by the green line. Energy consumption during the day is also reduced, as the EES is not needed to be charged to provide additional energy for up balancing purpose. The cost for meeting the updated load profile when the EES helps to shift the load is 414 million $. By adding the balancing cost onto it, the total system cost for 1st of January is 417.2 million $. Compared with the total costs under both cases given in Table II, using EES to provide load shifting only apparently yields more saving than to provide both load shifting and 10-minute balancing services.

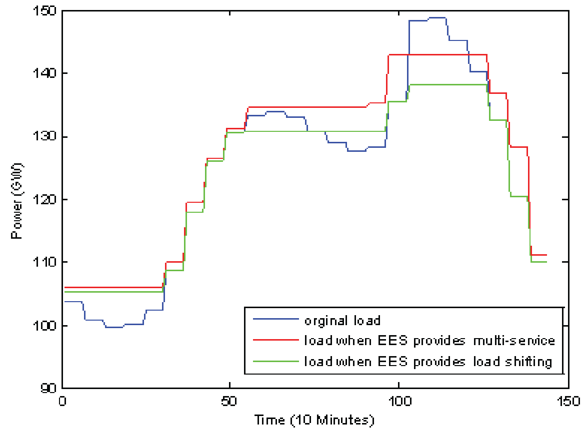

Figure 9. Comparison of load shifting capability of the EES between the system with multi-service provision and single service provision

Same annual economics calculation procedure carried out in Case 3 is applied to investigating the annual economics for the system using the EES to provide load shifting service only, and the annual cost for meeting the hourly load is found as 145079.66 million $. Although this is less than the load cost given in the third column of Table IV, due to the additional balancing cost, the overall saving for this case is in fact less than the case when the EES is used to provide multi-services. In other words, using the assumed EES to provide both load shifting and balancing services for the 2030 WECC load scenario is more profitable than to provide either of the two required services.

IV. CONCLUSION

This paper has presented a generic optimization model that explores the difficulty met by Electric Energy Storage (EES) systems when economic dispatch for multiple-service provision is at request. When such model is applied to solving the economic dispatch problem of using EES to provide both load shifting and 10-minute balancing services for one 2030 load scenario of WECC, the methodology takes into account the dynamics of the cost function which is represented by a nonlinear function of hourly load. Economic performance for the according energy system has been studied and analyzed. Results shows using the EES to provide load shifting and 10-minute balancing service results in significant saving for the system operation. Although the economics of such study are very case sensitive, the method presented in this paper may be useful to evaluate the economics of EES and to optimally size the EES when specific power system information and service requirements are already defined.

ACKNOWLEDGMENT

The authors gratefully acknowledge the contributions of Michael C.W. Kintner-Meyer, Yousu Chen, Xinxin Guo, Shuai Lu, all with the Energy Technology Development Group of PNNL, for valuable discussions and ideas.

REFERENCES

[1] B. B. Lundin, U. L. M, “Electricity Storage," EUSUSTEL project. Deliverable of Task 3.3.8 Work Package 3. [Online] Available: http://www.eusustel.be/public/documents_publ/WP/WP3/EUSUSTEL%20WP3%20Storage.pdf

[2] C.D. Parker, "Lead-acid battery energy storage systems for electricity supply networks," *Journal of Power Sources,* Nov. 2001.

[3] E. Zvingilaite, H.K. Jacobsen, “Overview of Optimal Market Response Options," RESPOND Report D5, une 2008, [Online] Available: http://www.ecn.nl/docs/library/report/2009/o09017.pdf

[4] C. Binding, D. Gantenbein, and P. B. Andersen, “Electricl Vehicle Fleet Integration in the Danish EDISON Project- A Virtual Power Plant on the Island of Bornholm, ”. accepted and to be by PES General Meeting 2010, Minneapolis, Mn USA, July, 2010

[5] C.J. Greiner, M. Korpas, T. Gjengedal, “Optiaml Operation of Energy Storage Systems Combinded with Wind Power in Short-Term Power Markets,”, proceedings of EWEC2009, Marseille, France, March, 2009

[6] E. D. Castronuovo and J.A. Lopes, “Optimal operation and hydro storage sizing of a wind-dydro power plant,” Internal Journal of Electricl Power & Energy Systems, vol. 26, iss. 10, December 2004, pp.771-778

[7] B. Lu and M. Shahidehpour, “Short-Term Scheduling of Battery in a Grid-connected PV/Battery System,” IEEE Transaction on Power Systems, 2005, vol. 20, part 2, pp. 1053-1061

[8] C.H. Lo, M. Anderson, “Economic Dispatch and Optimal Sizing of Battery Energy Storage Systems in Utility Load-leveling Operations,” IEEE Transaction on Energy Conversion, 1999, vol. 14, iss. 3, pp. 824-829

[9] A. Oudalov, R. Cherkaoui, A. Beguin, “Sizing and Optimal Operation of Battery Energy Storage System for Peak Shaving Application,”Proceedings of Power Tech 2007, Lausanne, Switzerland, July, 2007

[10] PROMOD: http://www.ventyx.com/analytics/promod.asp

[11] Matlab Nonlinear Optimization Toolbox: http://www.mathworks.com/p-roducts/optimization/

www.elektro.dtu.dk/cet

Department of Electrical Engineering
Centre for Electric Technology (CET)
Technical University of Denmark
Elektrovej 325
DK-2800 Kgs. Lyngby
Denmark
Tel: (+45) 45 25 35 00
Fax: (+45) 45 88 61 11
E-mail: cet@elektro.dtu.dk

[Skriv: ISBN XX-XXXXX-XX-X (eller slet)]